Development of Human Factors Guidelines for Advanced Traveler Information Systems (ATIS) and Commercial Vehicle Operations (CVO): CVO Driver Fatigue and Complex In-Vehicle Systems

PUBLICATION NO. FHWA-RD-96-151 **OCTOBER 1997**

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
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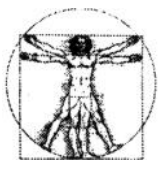
McLean, VA 22101-2296



FOREWORD

This report is one of a series of reports produced as part of a contract designed to develop precise, detailed human factors design guidelines for Advanced Traveler Information Systems (ATIS) and Commercial Vehicle Operations (CVO). During the analytic phase of the project, research issues were identified and rated by 8 human factors experts along 14 separate criteria. The goal of the experimental phase was to examine the highest rated research issues that can be addressed within the scope of the project. The 14 experiments produced in that phase reflect the results of those ratings.

This report documents a study that was performed to determine the effects of commercial driver fatigue and complex system operation on driver performance.

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Technical Report Documentation Page

1. Report No. FHWA-RD-96-151	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle DEVELOPMENT OF HUMAN FACTORS GUIDELINES FOR ADVANCED TRAVELER INFORMATION SYSTEMS (ATIS) AND COMMERCIAL VEHICLE OPERATIONS (CVO): CVO DRIVER FATIGUE AND COMPLEX IN-VEHICLE SYSTEMS		5. Report Date October 7, 1997 6. Performing Organization Code	
7. Author(s) Jaesik Lee, Thomas A. Dingus, Michael Mollenhauer, Timothy Brown, Vicki L. Neale		8. Performing Organization Report No.	
9. Performing Organization Name and Address Center for Transportation Research Virginia Polytechnic Institute and State University 1700 Kraft Drive, Suite 2000 Blacksburg, VA 24061-0536		10. Work Unit No. (TRAIS) 3B4C 11. Contract or Grant No. DTFH61-92-C-00102	
12. Sponsoring Agency Name and Address Office of Safety and Traffic Operations R&D Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code	
15. Supplementary Notes Contracting Officer's Technical Representative (COTR) – M. Joseph Moyer, HRDS; Thomas M. Granda, HRDS (formerly with SAIC)			
16. Abstract As one of a series of studies aimed at gathering data to develop human factors design guidelines for Advanced Traveler Information Systems (ATIS) and Commercial Vehicle Operations (CVO), the present study utilized a driving simulator to study CVO drivers and (1) the effects of driver fatigue and (2) the effects of mental workload on objective and subjective indices of driver performance and opinion. Fatigue was induced through sleep deprivation and through a 90-minute simulator drive. Mental workload was manipulated through driving task load and ATIS complexity. Although the results indicated degraded driving performance under the sleep-deprived condition, performance on ATIS-related tasks was not affected by sleep deprivation. The implication of this and other results are detailed.			
17. Key Words Advanced Traveler Information System, ATIS, Commercial Vehicle Operation, CVO, fatigue, mental workload		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 79	22. Price

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	**ha**
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact)				
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

TABLE OF CONTENTS

Page

EXECUTIVE SUMMARY 1

CHAPTER 1: INTRODUCTION 3
FATIGUE 4
Length of Work Period 5
Sleep and Rest Periods 5
Circadian Rhythms 5
MENTAL WORKLOAD 6
ATIS AND CVO 6
OBJECTIVES AND HYPOTHESES OF THE STUDY 7

CHAPTER 2: METHOD 9
SUBJECTS 9
APPARATUS 9
ATIS Information Presentation Equipment 10
HUD Display Format 10
Response Button and Turn-Signal Lever Format 11
Experimental Design 11
Overview of Independent Variables 11
Sleep Deprivation. 12
Time-on-Task. 12
ATIS Complexity. 12
Driving Load. 13
Display Modality. 13
Overview of Dependent Variables 13
Driving Performance Measures. 14
ATIS Task Performance. 15
Fatigue Measures. 15
Subjective Measures of Mental Workload. 17
Driving Scenarios 17
PROCEDURE 18

CHAPTER 3: RESULTS AND DISCUSSION 21
DRIVING PERFORMANCE 21
Driving Speed 21
Longitudinal Acceleration 22
Lane Position Deviation 22
Lane Deviation Frequency 25
ATIS TASK PERFORMANCE 28
Response Latency 28

TABLE OF CONTENTS (continued)

Page

Error Frequency 31
FATIGUE ASSESSMENT 31
Slow Eye Closure Measurement 31
Frequency of Complete Eye Closure 31
Mean Eye Lid Position 32
Percentage of Eye Ramp Closure Time 33
Subjective Fatigue Rating 33
Fatigue Levels Before and After the Experiment 33
Subjective Fatigue Rating at Each Experimental Condition 36
WORKLOAD ASSESSMENT 37
Time Stress 37
Visual Effort 39
Psychological Stress 39

CHAPTER 4: GENERAL CONCLUSIONS 43

APPENDIX A 45

APPENDIX B 60

APPENDIX C 61

APPENDIX D 62

APPENDIX E 63

REFERENCES 64

LIST OF FIGURES

Figure		Page
1.	General ATIS HUD format	10
2.	The response button and turn-signal format for the ATIS task	11
3.	Examples of ATIS complexity condition	13
4.	Difference between an slow eye closure and a blink as a function of time	16
5.	Effect of time-on-task on driving speed variability	21
6.	Relationship between time-on-task and ATIS complexity on the standard deviation ratings of lane deviation for the sleep-deprived condition	23
7.	Relationship between sleep deprivation/sleep condition and ATIS complexity on the standard deviation ratings of lane deviation	24
8.	Effect of time-on-task on the standard deviations of lane deviation at the non-sleep-deprived condition	25
9.	Relationship between time-on-task and driving load on the number of lane deviations	27
10.	Relationship between ATIS complexity and driving load on the number of lane deviations	28
11.	Relationship between time-on-task and ATIS information modalities on response latency in the ATIS task	29
12.	Relationship between ATIS complexity and driving load on response latency for the ATIS task	30
13.	Relationship between ATIS complexity and ATIS information modality on response latency in the ATIS task	30
14.	Effect of time-on-task condition on the number of complete eye closures	32
15.	Relationship between ATIS complexity and time-on-task condition on the mean eye ramp position	33
16.	Effect of sleep deprivation on subjective rating on drowsiness when measured before and after the experiment	34
17.	Effect of sleep deprivation on subjective rating on difficulty in concentration when measured before and after the experiment	35
18.	Effect of sleep deprivation on subjective rating on physical impairment when measured before and after the experiment	35
19.	Effect of time-on-task condition on the level of subjective fatigue when measured during the experiment	37
20.	Relationship of time stress rating between ATIS complexity and driving load at each time-on-task condition	38
21.	Relationship of psychological stress rating between ATIS complexity and driving task at each time-on-task condition	40

LIST OF TABLES

Table		Page
1.	Driving load	13
2.	Multivariate analysis of variance for mean value of driving speed	45
3.	Multivariate analysis of variance for standard deviation ratings of driving speed	46
4.	Multivariate analysis of variance for standard deviation ratings of longitudinal acceleration	47
5.	Multivariate analysis of variance for standard deviation ratings of lane position	48
6.	Two-way analysis of variance for lane position deviations at the sleep-deprived condition	48
7.	Two-way analysis of variance for lane position deviations at the non-sleep-deprived condition	49
8.	Multivariate analysis of variance for response latency in ATIS task	49
9.	Multivariate analysis of variance for mean eye ramp closure	51
10.	Multivariate analysis of variance for mean eye ramp position for sleep deprivation, non-sleep-deprived condition	52
11.	Multivariate analysis of variance for mean eye ramp position for sleep deprivation, no sleep condition	52
12.	Multivariate analysis of variance for mean percentage of time when the eye ramp was 80 percent to 100 percent closed	53
13.	Multivariate analysis of variance seven-point subjective fatigue rating during experiment	54
14.	Multivariate analysis of variance for subjective time stress rating	55
15.	Two-way analysis of variance for subjective time stress rating at the first time-on-task condition	56
16.	Two-way analysis of variance for subjective time stress rating at the second time-on-task condition	56
17.	Two-way analysis of variance for subjective time stress rating at the third time-on-task condition	56
18.	Multivariate analysis of variance for subjective visual effort rating	57
19.	Multivariate analysis of variance for subjective psychological stress	58
20.	Two-way analysis of variance for subjective psychological stress rating at the first time-on-task condition	59
21.	Two-way analysis of variance for subjective psychological stress rating at the second time-on-task condition	59
22.	Two-way analysis of variance for subjective psychological stress rating at the third time-on-task condition	59

LIST OF ABBREVIATIONS

ATIS . . . . . Advanced Traveler Information Systems
CRT . . . . . Cathode Ray Tube
CVO . . . . . Commercial Vehicle Operators
DOT . . . . . Department of Transportation
FHWA . . . . . Federal Highway Administration
HUD . . . . . Head-up Display
ITS . . . . . Intelligent Transportation Systems
LCD . . . . . Liquid Crystal Display
MANOVA . . . . . Multivariate Analysis of Variance
MSE . . . . . .Mean Squared Error
s . . . . . Seconds
STI . . . . . System Technology Inc.
SWAT . . . . . Subjective Workload Assessment Technique
TOT . . . . . Task-On-Time

EXECUTIVE SUMMARY

Battelle's Human Factors Transportation Center is carrying out a project for the U.S. Federal Highway Administration (FHWA) to develop human factors design guidelines for the Advanced Traveler Information Systems (ATIS) and Commercial Vehicle Operations (CVO) components of the Intelligent Transportation Systems (ITS). The objective of the current study was to evaluate the effect of commercial driver fatigue and mental workload on driving performance and behavior while operating a driving simulator equipped with an ATIS.

A lower-fidelity driving simulator at the University of Iowa was used to study (1) the effects of driver fatigue and (2) the effects of mental workload on objective and subjective indices of driver performance and opinion. The simulator used was fixed-base, and the software was developed by Systems Technology, Incorporated (STI). CVO drivers from the Iowa City, Iowa, area participated in the study. Driver fatigue was manipulated in two ways. First, all commercial drivers participated in the experiment in sleep-deprived and non-sleep-deprived conditions. Second, for each of these sleep deprivation conditions, drivers drove the simulator for 90 minutes, thereby inducing time-on-task-related fatigue. Mental workload was also manipulated in two ways. First, the simulation was programmed to provide two types of driving task load: low load conditions, which consisted of wide lanes and high-speed curves, and high load conditions, which included narrow lanes and tight curves. Second, three levels of ATIS complexity were presented: low, medium, and high complexity information. Complexity was manipulated by varying the number of information items. During the simulation, ATIS information was presented both visually and aurally.

The results indicated degraded driving performance under the sleep-deprived condition compared with the non-sleep-deprived condition. However, performance on ATIS-related tasks was not affected by sleep deprivation. In fact, it appeared that use of an ATIS by fatigued drivers enhanced alertness, which in turn resulted in relatively equal performance compared with the less fatigued drivers. Drivers' fatigue increased as the simulation progressed. Based on various driving performance measures, eye closure measurements, and subjective ratings, drivers exhibited behavior associated with greater fatigue later in the simulation. The complexity of the ATIS had little impact on the driving performance-dependent measures. However, subjective ratings of mental workload increased as ATIS complexity increased. Driving load, or the complexity of the driving environment, also had an impact on subjective ratings for mental workload and fatigue. In addition, drivers had generally poorer driving performance measures in high driving load environments compared with low driving load environments. The display modality manipulation showed the auditory modality had shorter response time compared with the visual modality. However, response time for the auditory modality increased more markedly, in comparison with the visual modality, as the complexity of the message increased.

The results of this experiment can be summarized into several major ATIS/CVO design guidelines:

- Fatigue-related driving performance effects can be mitigated to some extent when drivers interact with an ATIS. Therefore, drivers should not be discouraged from ATIS interaction under fatiguing conditions.

- It appears that commercial drivers will be able to respond to safety-related ATIS information, as well as maintain general ATIS task performance, while moderately fatigued.
- Increasing ATIS complexity can increase mental workload, thus decreasing driving performance. However, commercial drivers are able to operate ATIS systems of moderate complexity with no apparent degradation in performance.
- If practical, presentation of ATIS messages should occur when driving performance demands are minimal. Particularly in the case of CVO, some messages could be filtered and sequenced to aid commercial drivers by leveling task demands.

CHAPTER 1: INTRODUCTION

The trucking industry has experienced rapid growth in the past 50 years. This growth has brought about considerable changes in the work patterns of the truck driver. The introduction of sophisticated management techniques, which emphasize cost-cutting and efficiency through the computer planning of loading, dispatching, and routing, has caused many small haulage companies to pressure drivers into rigorous work schedules and driving for extended periods of time. Legally, truckers can drive 10 hours per day for a maximum of 70 hours in 8 days. An additional 5 hours per day can be spent loading and unloading the truck. As a result, it is possible for truckers to drive 10 hours, rest 8 hours, load a truck for 5 hours, and drive another 10 hours before resting again.

The hours-of-service regulations, published in 1937 and adopted after the completion of a research study in 1941, were meant to protect drivers from extremely long hours on the road. Abuse of the regulations is a continual concern, especially in long-distance operations (Transportation Research and Marketing, 1985). Although some rule changes have been implemented during the past 55 years, they have been more procedural than substantive and have had little impact on the actual hours worked. Many motor carriers believe that major changes in industry operations since the 1930s (e.g., highway and vehicle improvements providing greater driver comfort and reduced physical demands) have not been acknowledged in the hours-of-service rules.

As outlined by Ryder (1990), the National Motor Transport Data Base interviewed 24,000 truckers and found that more than 37 percent said they were exceeding the 10-hour daily limit. Based on this finding, it is no surprise that driver fatigue is the leading cause of heavy truck accidents. A report from the Bureau of Motor Carrier Safety observed that up to 42 percent of truck accidents between 1973 and 1976 were caused by the driver dozing, falling asleep, being inattentive, or being momentarily distracted (Ryder, 1990).

Both commercial and private drivers know what it feels like to “doze-off” while driving. However, the problem is more urgent for commercial vehicle drivers because they drive hundreds of hours and thousands of miles. While the task of operating a heavy vehicle is not itself physically fatiguing, the monotony of driving, together with the hum of the engine, the lights of passing cars at night, or the bright sunshine in daytime, create an environment conducive to vigilance decrement. Not only do truckers put in long hours, but they also drive at all times of the day and night, thereby disturbing their sleep patterns (circadian rhythms) and producing weariness.

The task of operating a heavy vehicle is more complex than operating a private vehicle such as a car. For example, compared with operators of private vehicles, commercial drivers spend more time scanning the side mirrors to monitor the trailer’s tracking and watch for passing vehicles. Also, compared with private drivers, the large size of heavy vehicles and their reduced ability to accelerate and decelerate means that commercial drivers must plan and maneuver far in advance. In addition, compared with private vehicles, tractor-trailers typically have additional gauges that require operator monitoring (e.g., air pressure and transmission temperature). These differences

between private and heavy vehicles suggest that more mental effort is required of CVOs than operators of private vehicles.

The purpose of the present study is to investigate the combined effect of driver fatigue and mental workload on driving performance and other behavior during interaction with complex in-vehicle information systems, specifically ATIS. The goal of this research is to provide data to aid the ATIS designer in developing systems that do not significantly increase level of fatigue and mental workload of commercial drivers.

FATIGUE

"Fatigue" is generally used in everyday speech to describe a general set of feelings or sensations, including any one or more of the following: tiredness, sleepiness, boredom, or physical weariness. However, the term is too vague to be useful in scientific research on fatigue. For example, it does not specify cause, mechanism, or effects of fatigue on behavioral consequence. For this type of research, it is necessary to state fatigue in terms of an operational definition.

Muscio (1921) started researchers thinking about the necessity of defining fatigue. He argued that without an acceptable definition and reliable measures, it was impossible to conduct fatigue tests. The earliest definitions, such as ones by Bills (1934) and Platt (1964), separate fatigue into three different types: *subjective fatigue*—the feeling of being tired, *physiological fatigue*—as determined from bodily changes, and *objective fatigue*—when performance on a task shows a progressive deterioration.

Bartley and Chute (1947) agreed with Muscio, assigning the effects of fatigue into three broad categories: measures of *work output,* which are performance data and include declines in all types of overt activity; *impairment,* which measures physiological changes at the tissue level, including changes in neural and motor functions; and *fatigue,* which is the subjective feeling of bodily discomfort and aversion to effort. Cameron (1973) has taken a more recent look at fatigue, especially in relation to driving. He states the importance of anxiety, and examines the link between fatigue and sleep disturbances. Cameron suggests that fatigue is a generalized response to stress over time.

Most researchers will agree that there is not a single state called "fatigue," and its meaning in any one context has to be understood from the circumstances of that context. Ivan Brown (1994) stated that three main factors determine whether humans can continue performing work at an acceptable level in the long term: (1) the length of continuous work spells and daily duty periods; (2) the lengths of time away from work that are available for rest and for continuous sleep; and (3) the arrangement of duty, rest, and sleep periods within the 24-hour cycle of daylight and darkness, which normally determines individuals' circadian rhythms. For drivers who work shifts or irregular hours over extended periods, the effects of these three factors are not independent.

Length of Work Period

A number of surveys from different countries have shown very similar results regarding the number of hours worked by truck drivers per week. Fifty-four percent of drivers in Germany drive 30-50 hours per week, 41 percent of drivers from the United States drive 8-12 hours per day, and one-third of drivers from Ireland reported exceeding 12 hours of driving in one day (McDonald, 1984). For a driver, however, the day is not made up solely of driving. Many of them supervise, or are responsible for, the loading and unloading of their vehicles and spend their spare time doing maintenance work on their vehicle.

Sleep and Rest Periods

Sleep, when it can be obtained by commercial drivers, is often poor. Compared with private drivers, truck drivers typically get fewer daily hours of sleep and a greater proportion of shorter sleep periods (McDonald, 1984). Many truck drivers try to sleep in sleeper berths in the backs of their trucks. Unfortunately, due to insufficient insulation, their cabs are usually too hot in the summer and too cold in the winter for adequate sleep. There is also the problem of noise due to passing trucks, as well as noise from the truck's own motor if it is necessary to keep the truck running. In addition, some states (e.g., Virginia) only allow trucks to park in rest areas for short periods, even at night.

In a study done by Mackie and Miller (1978), it was found that the sleep period during off-duty periods was more than 9 hours compared with around 6 hours in the truck berth, which suggests that the off-duty period is used to catch up on the "sleep debt" accumulated during the working week. In addition, irregular operations force drivers to operate during night hours when they are most likely to be tired. A 1972 study done by the Department of Transportation (DOT) found that drivers were most tired between 2 and 7 a.m., yet drove most frequently during this period.

Circadian Rhythms

People have internal biological clocks with a natural cycle of about 25 hours in length. This clock has to be reset everyday so that its cycle coincides with the 24-hour-long day. Physical and social time cues are responsible for the normal resetting of what we term the circadian system. Research indicates that because many circadian biological systems are quite resilient to an abrupt change in routine, synchrony with many work schedules may be quite difficult to attain (Wever, 1979). This is especially true in the case of the third shift worker (as is the case with many truck drivers) whose off time repeatedly thrusts him or her into a daytime-oriented society. Assuming that our circadian rhythm system determines how well we can perform and when we require sleep, it is reasonable to suggest that night work is a problem in the sense that it calls for behavior that does not match the biological clock.

Harris and Mackie (1972) suggested that diurnal variations in the level of physiological arousal occurred in professional truck drivers who drove during both daytime and nighttime hours, and noted that over 50 percent of a sample of accidents involving "sleepy or inattentive" drivers

occurred between 12 and 8 a.m., when physiological indices of arousal are generally at their lowest levels.

MENTAL WORKLOAD

Although there is no universally accepted definition of mental workload (McCloy, Derrick, and Wickens, 1983), the basic notion is related to the ratio of the amount of resources available within a person and the amount of resources demanded by the task situation. This means that mental workload can be changed by altering either the amount of resources available within the person to perform a task or the demands made by the task on the person.

The mental workload associated with the driving task can be thought of several ways. For example, maintaining a lane position variability of 0.25 m will produce a higher level of mental workload than maintaining variability of 0.5 m. However, the amount of mental workload in this example will depend on the experience of the driver. That is, the same task will be perceived differently by different drivers, giving rise to different levels of subjective mental workload. For example, a novice driver will make far more effort to drive in high-density traffic than an experienced driver. Even though the task demands are the same, the novice's level of mental workload will be much higher. Similarly, such a task will be more difficult for a driver when he or she is tired than when he or she is refreshed. Thus, subjective mental workload is related not only to task complexity, but also to effort and arousal.

CVO drivers must perform a relatively complex interrelated set of tasks, which increases their mental workload. At the most basic level are those tasks involved in the physical control of the vehicle , i.e., steering it along the driving lane, and maintaining adequate speed through the use of the brake, clutch, gears, and accelerator. At the same time, the driver has to respond appropriately to a range of relatively discrete signals; these include road signs, obstacles in the roadway, and the signals and movements of other road users. The commercial driver also interacts with other vehicles in a variety of maneuvers such as following, overtaking, passing, lane merging, and negotiating with other vehicles at intersections. Such maneuvers involve the driver's ability to make critical decisions on the basis of what is often imprecise perceptual information, as well as interpretations of other drivers' intentions. The commercial driver is also occasionally confronted with emergency situations where the consequences of an action (or inaction) are potentially disastrous, and where tolerances of error are low and opportunities for learning are limited. Such situations include a sudden blow-out at high speed, brake failure, skidding on unexpected ice patches, and a child running into the road.

ATIS AND CVO

The term ITS applies to systems that involve integrated applications of advanced surveillance, communications, computer, and display/control process technologies, both in the vehicle and on the highway. The essence of ITS is to make significant improvements in mobility, highway safety, and productivity by building transportation systems that draw upon advanced electronic technologies and control software. Two major areas of ITS development are ATIS and CVO systems. ATIS systems encompass a number of currently available or developing features for

both private and commercial drivers. Examples include route guidance and navigation systems, in-vehicle signing systems, in-vehicle signaling and warning systems, and electronic log books for truckers.

According to an article by Sturgess (1991), commercial vehicle operators are the leading edge users of available ITS technologies, such as automatic vehicle location, tracking, two-way communication, and in-vehicle text and map displays. The use of high-technology in vehicles will enormously increase the amount of information presented to a driver. Although companies have begun to invest in these types of technologies, relatively little research has been conducted to investigate the impact these systems may have on fatigue and mental workload. As such, there is a need for human factors research that investigates aspects of information processing by commercial drivers, whose driving task is already complicated. It is believed that research of this nature can lead to guidelines that aid ATIS designers in developing safe and effective systems that do not add to the fatigue and mental workload currently experienced by this driving population.

OBJECTIVES AND HYPOTHESES OF THE STUDY

Since commercial drivers often endure more fatigue and more mental effort than other drivers, it is important to understand how adding a complex in-vehicle information system might impact their driving performance. The major objective of the study is to determine how fatigue impacts a commercial driver's ability to interact with complex in-vehicle systems. In fact, an ATIS system might: (1) enhance driving performance by increasing arousal and reducing fatigue, or (2) decrease performance by overloading the driver under circumstances of fatigue.

There are several hypotheses associated with how fatigue impacts a commercial driver's ability to interact with complex in-vehicle systems, driving performance, and behavior at various levels of mental effort. In addition, several assumptions should be addressed. First, it is assumed that commercial drivers will reveal the same driving characteristics while driving a lower-fidelity truck cab and simulator as they would a truck. Second, it is anticipated that sleep deprivation and time-on-task (TOT) will result in increased fatigue. Third, it is assumed that increase in task complexity and driving load will result in increased mental workload.

Based on these assumptions, the hypotheses of the present experiment are as follows:

- If the ATIS increases arousal and reduces fatigue, drivers will experience no degradation in driving performance.
- In contrast, if an ATIS system overloads the driver, driving performance will be decreased under circumstances of fatigue.

Past research has investigated mental workload by manipulating task complexity (e.g., Albanese, 1977; Wickens, 1992). Research has shown that both very high mental workload and very low mental workload cause performance decrement. If the operator has to monitor too many channels or complete too many tasks at once, performance on the task(s) degrades. However, task performance will also degrade if the operator is given too little to do. Therefore, allotting the correct task load for optimum performance is very difficult and extremely important. Driver fatigue, whether it is due to sleep deprivation and interrupted circadian rhythms or mental effort

and workload, is a very important issue that needs to be addressed. With advancing technology introducing computerized systems into commercial vehicles, an examination of how operators will manage the resulting additional information is required. It is feasible that additional information could be an added stressor, or a tool to decrease boredom and the effects caused by lack of sleep. Hundreds of studies have looked at fatigue and mental workload individually, but very few have looked at the combined impact on multiple tasks such as driving and interacting with an ATIS.

Although a number of navigation and information systems have been conceptualized and developed, and many studies have recognized the higher cognitive processing requirements imposed on commercial vehicle drivers, few empirical evaluations have provided evidence about the effect that in-vehicle systems have on driving and behavioral performances while the commercial driver is fatigued or cognitively highly loaded. Providing insight into these issues is a primary objective of this research.

CHAPTER 2: METHOD

SUBJECTS

Ten drivers (eight males and two females) with a mean age of 38.2 years were recruited from trucking organizations in the Iowa City area. All met the study qualifications, which included having a current valid CVO truck driver license, having experience driving a commercial vehicle (over 100,000 miles over-the-road), and passing medical screening questions. Drivers were paid $15 dollars per hour for time spent at the driving simulator center.

APPARATUS

Truck driver behavior was investigated using a low-cost, fixed-base simulator located at the University of Iowa. The simulation software was developed by System Technology, Incorporated (STI) and projected on a screen with a 40° by 50° field of view. The cab interior housed a suite of displays and controls that are typically found in an automatic transmission heavy vehicle. Additional displays included an in-dash programmable liquid crystal display (LCD), a head-up visual display, and an auditory display. The ATIS stimulus materials were presented via these displays.

Because noise and vibration are important environmental factors for fatigue and performance of the truck driver's environment, the cab was instrumented to induce noise and vibration into the vehicle cab. The playback system hardware, which was equipped to provide vehicle noise and vibration, consisted of a musical instrument sound sampler, a powerful audio amplifier, a studio monitor loudspeaker, and a mass driver-type audio transducer. The sound samples were played back using the sampler. Some parameters of the sound were controlled in real-time by software running on a PC. The sound samples were amplified and reproduced through the loud speaker, which was mounted under the hood facing the firewall of the vehicle cab, and through the mass driver, which was mounted under the driver's seat.

The sound samples were recorded from a semi-tractor as it was driven along a highway. Two sets of sound samples were recorded: (1) engine samples and (2) tire/road samples. The engine samples were recorded at different engine rpms using a conventional microphone. The sounds were played back through the loudspeaker with an rpm ranging between 600 and 1,800. The tire/road samples were recorded with the truck moving at several different speeds. The mass driver transducer, which was mounted under the seats, served as the recording transducer. These sounds were later played back through the same transducer. The speed range of recording was 5 mi/h to 55 mi/h. For the tire/road sounds, the frequency response of the mass driver was 5 Hz to 20 kHz. For the engine sounds, the frequency response of the loudspeaker was 40 Hz to 20 kHz. For both types of sounds, the digital audio tape recorder used to record the samples had a frequency response of 10 Hz to 20 kHz.

ATIS Information Presentation Equipment

HUD Display Format

A head-up display (HUD) was designed to provide ATIS information within the simulator. The LCD that was used measured 15 cm x 12 cm. The display was mounted on the upper-center dashboard of the vehicle (about 30 cm right from the subjects' straight viewing point). This location prevented the display from masking the driving scenery and required drivers to scan the display by moving their eyes from the driving scene to the dash area.

The format of the ATIS HUD is presented in figure 1. In general, the display consisted of textural messages and graphical icons. The display was divided into nine distinct "zones" where information was presented (see example in figure 3). Navigation directions (i.e., a simple map with directional arrows), and the distance in miles from the current location to a designated intersection were provided in the Navigation Window Zone. Designated street names were presented at either side of the Text Zone 1 (right or left) according to the direction of a turn. For example, if a directional arrow indicated a right turn, the name of the street to be turned onto was presented at the right side in Text Zone 1. Alternatively, if a directional arrow indicated a left turn, the name of the street to be turned onto was presented at the left side of Text Zone 1. Text Zone 2 included miscellaneous vehicle status information (e.g., engine temperature). The name of the street on which the trucker was currently driving was presented in Text Zone 3. A digital speedometer indicating the subject's current driving speed was provided in the Speedometer Zone. Road and vehicle signing information was presented in Icon Zone 2. A 55 mph speed limit sign, which was presented for the duration of the experiment, was located in Icon Zone 3.

<table>
<tr><td>Text Zone 1 (Left)</td><td rowspan="2">Navigation Window Zone</td><td>Text Zone 1 (Right)</td></tr>
<tr><td>Icon Zone 1</td><td>Icon Zone 2</td></tr>
<tr><td rowspan="2">Speedometer Zone</td><td>Text Zone 3</td><td rowspan="2">Icon Zone 3</td></tr>
<tr><td>Text Zone 2</td></tr>
</table>

Figure 1. General ATIS HUD format.

Response Button and Turn-Signal Lever Format

Figure 2 outlines the response button and turn-signal lever format used in the experiment. Four response buttons were located on the middle section of the steering wheel. The top two response buttons were labeled "V" and "R." The bottom two response buttons were not used for the current study and were covered with black tape. As drivers were presented with ATIS information, their task was to press the appropriate button as quickly and accurately as possible. The button to be pressed depended on the type of ATIS information presented. For information presented on the ATIS about the vehicle's condition (e.g., high engine temperature), drivers were required to press the upper left button labeled "V." For information presented that pertained to the driving task load (e.g., road construction ahead), drivers were required to press the upper right button labeled "R." Drivers were also instructed to operate the steering wheel with both hands, and to press the buttons using their thumbs (left thumb for button "V," right thumb for button "R").

Recall that navigation information was presented on the ATIS that informed drivers of upcoming turns. Drivers were instructed to signal a turn by operating the turn-signal lever according to the direction of the turn. Drivers indicated a right turn by pressing the turn-signal lever up, and a left turn by pressing the lever down. Drivers were told to indicate their turns when the ATIS indicated that the intersection was 0.2 miles ahead, and to turn off the signal when the ATIS indicated 0 miles to the intersection.

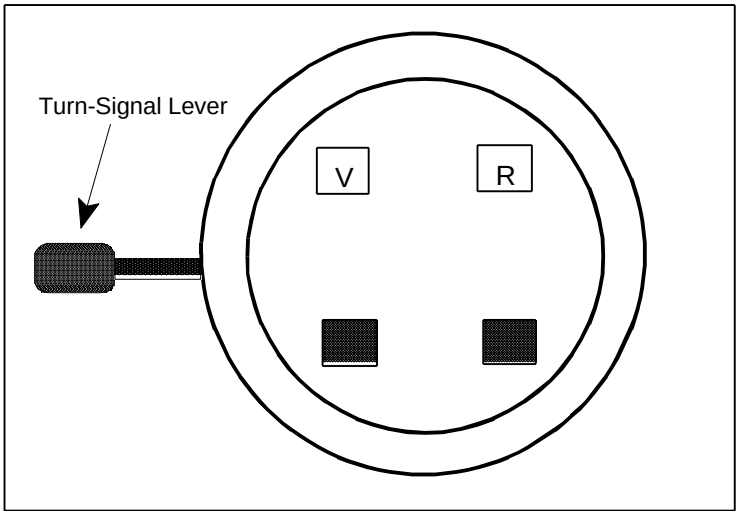


Figure 2. The response button and turn-signal format for the ATIS task.

Experimental Design

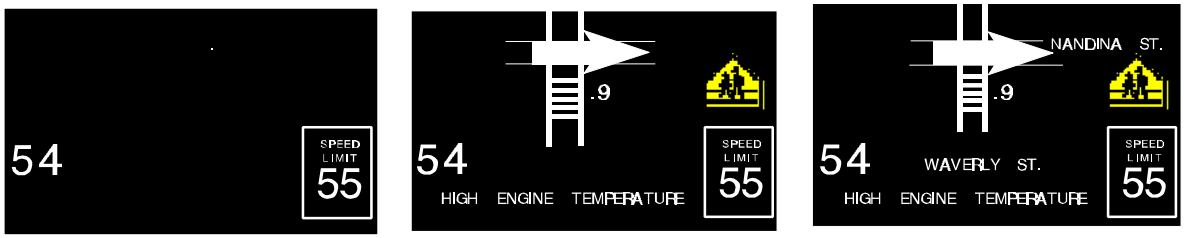
Overview of Independent Variables

A 2 x 3 x 3 x 2 complete factorial design was used. All of the independent variables were within-subjects and consisted of sleep deprivation, time-on-task, ATIS task complexity, driving load, and display modality. This set of variables is delineated below.

Sleep Deprivation. The purpose of the sleep deprivation variable was to introduce a method of inducing fatigue. There were two levels of the sleep deprivation variable: (1) non-sleep-deprived, where the drivers participated in the simulation soon after waking from a normal night's sleep, and (2) sleep-deprived, where the drivers participated in the simulation approximately 19 hours after waking from a normal night's sleep. In the non-sleep-deprived condition, drivers participated in the experiment soon after arriving at the driving simulator center. In the sleep-deprived condition, drivers were instructed to arrive at the center approximately 12 hours after waking from a normal night's sleep. Before beginning the simulation, drivers were monitored at the center for an additional 7 hours to ensure that no stimulants (e.g., caffeine) were ingested.

Time-on-Task. Like the sleep deprivation variable, time-on-task was used to induce fatigue. For all drivers, the simulation consisted of 90 minutes of driving time. It was anticipated that 90 minutes of driving would be sufficient to induce some fatigue. To examine additional fatigue effects caused by the length of the simulation, time-on-task was divided into three levels: (1) first 30 minutes of driving, (2) second 30 minutes of driving, and (3) third 30 minutes of driving.

ATIS Complexity. The purpose of the ATIS complexity variable was to induce different levels of mental effort. During the simulation, drivers were required to perform tasks based on the information provided by the ATIS. To vary ATIS complexity, the amount of information provided on the ATIS differed. There were three levels of ATIS complexity: (1) low, (2) medium, and (3) high. It was anticipated that less information would induce lower levels of mental effort, and more information would elicit greater mental effort. Figure 3 presents the three levels of ATIS complexity, as reflected in the amount of information presented on the ATIS. The first ATIS screen (A) shows the low driving task load condition, where the ATIS had minimal information consisting of the posted speed limit and the driver's current speed. The second ATIS screen (B) shows the medium driving task load condition, where all of the information shown in ATIS screen A was included in ATIS screen B. In addition, ATIS screen B has vehicle status information (e.g., engine temperature), a single navigation map indicating distance to the next intersection, and road/vehicle signing. More specifically, ATIS information was presented in every 3,000 feet of driving distance either visually or auditorally. A total of eight stimuli were provided with the same number to each modality. Four pictorial road or vehicle information icons were also presented. Each icon remained until the next icon appeared (each icon remained for 6,000 feet of driving). The third ATIS screen C shows the high driving task load condition that includes all of the information in ATIS screen B in addition to names of both the current and upcoming streets. In addition, the high driving load included four navigation maps with current street name and destination. Different directions of turns were alternated in every 6,000 feet of driving. Sixteen icons were presented every 1,500 feet of driving distance. In addition, 24 information icons (12 in text format and 12 in the auditory channel) about either road or vehicle condition were randomly provided every 1,000 feet of driving distance.



A B C

Figure 3. Examples of ATIS complexity condition (A: low; B: medium; C: high).

Driving Load. Like the ATIS complexity variable, driving load was included to manipulate mental effort. This was accomplished by varying the driving environment in terms of lane width, traffic density, road curvature, and frequency of cross streets. There were two levels of driving load: (1) low and (2) high (see table 1). In the low driving load condition, each lane was 12 feet wide, there was "light" traffic in the opposite lane (about one vehicle in every 3,000 feet of driving distance), there were gradual curves (e.g., road curvature of 1.5E-8/feet), and there were few cross streets (one cross street every 3,000 feet of driving distance). In the high driving load condition, each lane was 10 feet wide, there was "heavy" traffic in the opposite lane (about 10 vehicles in every 3,000 feet of driving distance), there were tight curves (e.g., roadway curvature of 0.00015/degrees/foot), and there were multiple cross streets (approximately one cross street every 1,000 feet of driving distance). In addition, the high driving load condition included pedestrians (about one pedestrian in every 1,000 feet of driving distance).

Table 1. Driving load.

	Low Driving Load	**High Driving Load**
Lane Width	12 ft.	10 ft.
Traffic Density	1 vehicle/3000 ft. of travel	10 vehicles/3000 ft. of travel
Number of Cross Streets	1 street/3000 ft. of travel	3 streets/3000 ft. of travel
Curve Radius	gradual	tight

Display Modality. During the conduct of the study, subjects were asked to respond to a variety of roadway or vehicle condition monitoring messages by pressing an appropriate push button (as previously described). To determine the effects of different modalities of displayed information on reaction time and accuracy under differing conditions of fatigue, one-half of the alerting stimuli were presented via the auditory modality and one-half were presented only on the visual display. Since modality was changed between run segments, only the task response data were analyzed with respect to modality differences.

Overview of Dependent Variables

To investigate the effect of fatigue and mental effort on drivers' information processing abilities while using an ATIS, several dependent measures were analyzed. These dependent variables

consisted of measures of: (1) driving performance, (2) ATIS task performance, (3) fatigue, and (4) mental workload. Each of these dependent variables is described below.

Driving Performance Measures. Six driving performance measures were collected during the simulation. These consisted of: (1) driving speed, mean and standard deviation, (2) longitudinal acceleration due to the throttle or brake, (3) standard deviation lane position, (4) lane deviation frequency, (5) steering wheel angle, and (6) lateral acceleration. Each of these measures is described below.

Driving speed. Vehicle speed can be considered a vehicle state that, at some level, has to be held constant in most circumstances. Therefore, accuracy and variations in velocity were used to evaluate performance. Vehicle speed is a common dependent measure of driving performance, as driving speed is affected by changes in attention and workload. Previous research (e.g., Antin, Dingus, Hulse, and Wierwille, 1990) has shown that drivers adapt to increased task demand by modifying their behavior and driving more "cautiously." One way that this modification is exhibited is that vehicle velocity decreases as task demand increases.

In addition to the mean driving speed, variance in driving speed is also a valid measure of task demand. Monty (1984) found speed maintenance to be a sensitive measure of changes in the amount of attention demanded by secondary driving tasks. Drivers are required to make many small adjustments to throttle and brake inputs to maintain a constant speed while driving. As secondary tasks are introduced, driver attention resources are drawn away from maintaining this constant speed. The addition of secondary tasks decreases the number of throttle and brake adjustments made by the driver. When these throttle and brake adjustments are made less frequently, inputs of greater magnitude are inevitably required to maintain driving speed. Mean and standard deviation values of driving speed were collected every 100 feet of driving distance.

Longitudinal acceleration. Abrupt driving speed changes can also provide a sensitive measure of performance. For example, consider a driver driving a vehicle and performing a secondary ATIS-related task that requires him/her to look away from the driving scene. At some point, the driver glances back to the driving scene and realizes that an unanticipated event is occurring (e.g., a pedestrian crossing the road). The driver reacts to this event by quickly and firmly depressing the brake pedal. This reaction results in vehicle deceleration that is greater than occurs in normal braking situations. Mean values of longitudinal accelerations were measured every 100 feet of driving distance.

Standard deviation lane position. Unplanned lane deviations provide a valuable face-valid measure of driving task interference that has resulted in performance degradation. Standard deviation lane position values were collected every 100 feet of driving distance.

Lane deviation frequency. A lane deviation was defined as any part of the vehicle, for any length of time, crossing a lane boundary. Driving task interference can be measured via lane deviation frequency. Greater lane deviation frequencies suggest greater driving task interference.

Lateral acceleration. Abrupt lateral maneuvers are indicative of a vehicle that has drifted

away from the center of the lane due to driver inattention. Large lateral accelerations provide insight into the degree to which a vehicle is off-track and, therefore, the magnitude of inattention.

ATIS Task Performance. Two measures of ATIS task performance were collected: (1) reaction time, and (2) error rate in ATIS task completion. Both of these measures are outlined below.

Reaction time. Subjects were required to press one of two buttons on the steering wheel as quickly and as accurately as possible based on the type of information (e.g., vehicle condition or roadway) presented. Given that the information provided was a simple icon or phrase, reaction time probably reflected the subjects' awareness of the ATIS information; faster reaction time implies an improvement in situation awareness.

All ATIS information was presented immediately after an auditory cue (e.g., beep). To provide feedback that the driver's response had been made, a different auditory signal was provided. Reaction time was calculated by subtracting the time when the button was pressed from the time when the ATIS information was presented. In addition, a too-fast response (reaction time less than 500 ms) or a delayed response (reaction time longer than 5 s) was not included in the data analysis, and was regarded as an error. Incorrect responses (wrong response selections such as pressing button V when road information was presented, or vice versa) were treated as errors and also were excluded from the time data analysis.

Error rate in ATIS task. Using the same rationale for reaction time in the ATIS task, a smaller error rate would imply better understanding of information than would a larger error rate. Error rate, in combination with reaction time, also provides data on speed-accuracy trade-offs. Better performance in responding to the ATIS tasks can be defined by lower response latencies and lower error rates. Error rate was calculated by dividing the total number of error responses by the total number of responses required.

Fatigue Measures. In the present study, drivers' fatigue levels were assessed by: (1) slow eye closure and (2) subjective measures.

Slow eye closure measurements. The measurement of slow eye closure has been used in several studies of driver's performance while fatigued (e.g., Dingus, 1985). A slow or "eye ramp closure," where the eye lid slowly covers the eye, is different from a blink, which is an automatic reflex for lubricating the eye. Figure 4 illustrates the difference between these two eye closure types. As shown, a blink occurs faster than an slow eye closure.

Slow eye closure has been found to be a primary indicator of drowsiness and reduced performance capability. Erwin (1976) found that slow eye closure presented the most stable physiological indication of drowsiness and is highly correlated with driving performance measures such as lane deviation and steering wheel velocity. Other aspects of eye lid movement have been investigated with regard to driving performance while fatigued. For example, Dingus (1985) used average eye lid position to measure fatigue while driving. As this measure takes into account all fluctuations in eye position, and not just the closures, average eye lid position has the potential to be a more sensitive measure than ramp closure. Dingus (1985) also used the percentage of time

that a driver's eyes were 80 to 100 percent closed over the specified length of an experiment and found that both eye ramp measures (i.e., average eye ramp position and percentage of time) were highly correlated with driving performance (i.e., lane deviation) and therefore, were reliable indicators of impairment due to drowsiness.

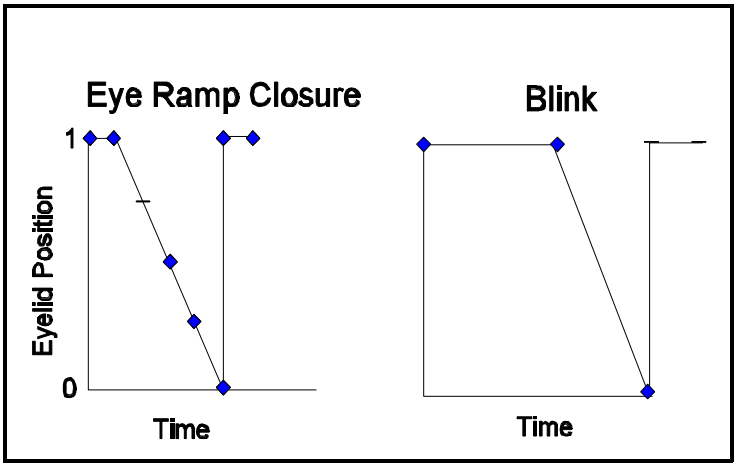


Figure 4. Difference between slow eye closure and a blink as a function of time.

For the present study, slow eye closure was continuously monitored through a low light level closed-circuit television camera that was focused on the driver's face. Change in ATIS and current driving scenarios were recorded simultaneously on the same video tape through a multi-plexed image so that each experimental condition could be distinguished. An experimenter monitored the subject's eye lid position post-hoc and adjusted the knob of a potentiometer to reflect this position. The analog signals of the eye lid position created by the potentiometer were then stored on a microcomputer for later analysis. Eye lid position data were sampled at 0.10-s intervals.

Three dependent measures were derived from the eye lid position signal: (1) frequency of complete eye closure, (2) mean value of eye lid position, and (3) percentage of eye closure time. The percentage of eye ramp closure time was calculated by dividing the duration of 80 to 100 percent eye ramp closure by the total duration of each experimental condition.

Subjective measures of fatigue. For the present study, two types of subjective fatigue rating scales were used. The first type was a multi-dimensional subjective scale (appendix A), which incorporated three dimensions of fatigue: drowsiness, difficulty in concentration, and projection of physical impairment. This multi-dimensional rating was used before and after the experiment to verify the effect of different sleep deprivation manipulations (e.g., whether at least 19 hours of sleep deprivation yielded a different level of fatigue) and to measure general changes in fatigue level after the experiment.

The second subjective measure of fatigue was a uni-dimensional, seven-point rating scale

(appendix B) (Pearson & Bayer, 1956). The numbers (one to seven) were assigned to different descriptions according to various levels of fatigue. Prior to beginning the experiment, drivers were trained on matching each number to its corresponding description. During the experiment, drivers were asked to verbally report to the experimenter the number that described his/her level of fatigue. This scale was administered after each experimental condition (after about 5 minutes of driving). The purpose of adopting this scale was to monitor the change in the subjective level of fatigue as a function of different experimental conditions.

Another type of subjective fatigue rating scale (revised from Yoshitake, 1971, and shown in appendix C) was a multi-item questionnaire to measure various dimensions of fatigue (drowsiness and dullness, difficulty in concentration, and projection of physical impairment). This scale was used both before the start of the experiment and after the experiment concluded. In both instances, drivers were seated at a desk while they completed the questionnaire. Subjective fatigue ratings were calculated by dividing the number of "Yes" answers by total number of items in each dimension for later analysis.

Subjective Measures of Mental Workload. Similar to the subjective measures of fatigue, a subjective mental workload measurement task was used to assess the mental workload demand of the driving tasks. With a modified version of the Subjective Workload Assessment Technique (SWAT) (Reid, Eggemeier, and Nygren, 1982), subjective ratings were collected at the end of each experimental drive. SWAT requires the subject to rate three dimensions of driving workload (visual effort, time stress, and psychological stress) as high, medium, or low.

Driving Scenarios

The simulated driving scenarios were developed using the STISIM scripting language. The driving environment used in both the high and low driving load conditions consisted of two-lane highways with cross streets occurring at intervals that might be seen in an urban or suburban area. All cross streets were labeled with street name signs that consisted of white letters on a green background. The street-name signs were mounted on posts on either the left or the right side of the road. In addition, the parameter of subjects' eye-height in the STI program was set to 8 feet above the ground for the purpose of simulating the truck driver's view point in a real driving situation.

Six different driving scenarios, each approximately 435,600 feet in length, were developed to test the six different combinations of ATIS complexity (i.e., low, medium, and high) and driving load (i.e., low and high). For example, a low ATIS complexity and low driving load combination consisted of driving in a straight lane while receiving information on current driving speed. The presentation of the six task types (i.e., low ATIS complexity x low driving load, low ATIS complexity x high driving load, medium ATIS complexity x low driving load, medium ATIS complexity x high driving load, high ATIS complexity x low driving load, high ATIS complexity x high driving load) were counterbalanced for the three different time-on-task presentations.

PROCEDURE

There were three parts to this experiment: (1) the orientation session, (2) the first experimental session, and (3) the second experimental session. Each session was completed on a different day. At the start of the first session (orientation session), drivers were given a summary of the experimental requirements and asked to complete an informed consent form (appendices D and E). Also at this time, each driver's qualifications for the study were checked to ensure that he or she met the minimum requirements. These requirements included having: (1) a current valid CVO license, (2) experience driving a commercial vehicle, (3) the required visual acuity, and (4) the required medical background. Once the background was completed, drivers were asked to drive the simulator for approximately 30 minutes. The driving scenario for the orientation session was similar to that of the experimental session, but without any additional task requirements (e.g., no ATIS tasks or subjective ratings of fatigue). One of the primary purposes of the orientation session was to screen participants for simulator sickness. Drivers who showed no signs of simulator sickness, and agreed to continue their participation in the experiment, were scheduled for the next two sessions. Note that for consistency, all drivers were scheduled for the experimental sessions after a normal driving shift (e.g., 5-day work week). It was assumed that this might lead to consistent and greater levels of fatigue compared with using drivers after a day off.

The experimental conditions, including introduction of the ATIS, occurred in the next two sessions. For one of these sessions, drivers were not sleep deprived, while for the other session they were sleep-deprived. Recall that sleep deprivation was counterbalanced such that five drivers were not sleep-deprived in the first session, but were sleep-deprived in the second session. The other five drivers were sleep-deprived in the first session, but were not sleep-deprived in the second session. Drivers who were not sleep-deprived arrived at the center after a reported normal night's sleep. Drivers who were sleep-deprived arrived at the center 12 hours after waking from a reported normal night's sleep and began their session 7 hours later. During this time, drivers were monitored so that no stimulants (e.g., caffeine) were ingested. Note that drivers who participated in the sleep deprivation condition first were scheduled for their next appointment no sooner than 48 hours after completing the first experimental session.

For each sleep deprivation condition, drivers were randomly assigned to one of the six driving scenarios. The presentation order of the driving scenarios was counterbalanced to minimize order effects.

Before the start of the first experimental session, drivers were instructed on the procedure for reporting their fatigue and workload ratings. This included outlining the meaning of each category and levels of mental workload in SWAT, and the numbers and matching descriptions in the uni-dimensional seven-point fatigue rating scale. Subjects were then asked to fill out the multi-dimensional subjective fatigue rating questionnaire (pre-experimental subjective rating) based on their current level of physical and mental fatigue. After completing the questionnaire, subjects were seated in the driver's seat and asked to adjust the seat and tilt steering wheel for their comfort. All controls were pointed out and functions were explained. Also at this time, the nature of the ATIS display format and the task requirements were explained.

During the practice session, drivers were trained on the simulator and encouraged to drive as they normally would. In addition, drivers were instructed to practice hard braking and extreme steering. Drivers were also tested on their ability to maintain target speeds and control the vehicle. The practice scenario provided drivers with all possible combinations of experimental conditions (e.g., different load conditions and different levels of ATIS complexity) in about 10 minutes of driving. Drivers continued on the practice course until they could perform the required tasks while committing no driving or ATIS task errors. In addition, drivers were asked if they were comfortable with the simulator or would like more practice. None of the drivers required a second practice session.

After the practice session, drivers drove each of the six experimental driving scenarios, counterbalanced over 18 experimental blocks. At the end of each experimental block, which consisted of about 5 minutes of driving, drivers were asked to report their level of mental workload (SWAT) and subjective fatigue level (uni-dimensional scale). The experimenter recorded these responses on the scoring sheet. At the end of the 90-minute driving session, drivers completed the post-test multi-dimensional subjective fatigue questionnaire.

CHAPTER 3: RESULTS AND DISCUSSION

In reporting ratings, a significance level of 0.05 was applied to all Multivariate Analysis of Variance (MANOVA), simple effect analyses including Paired T-Test for Post-Hoc comparisons, and Chi-Square tests for frequency analysis. For details of all analyses conducted, please refer to appendix A for the complete set of Multivariate Analysis of Variance tables.

DRIVING PERFORMANCE

Driving Speed

The MANOVA for mean driving speed (appendix A, table 2) indicated no significant result; drivers maintained the target driving speed consistently, independent of the experimental conditions. However, figure 5 shows that drivers had increased speed variance as time-on-task increased, $F(2,18) = 3.93$, $p<0.05$ (appendix A, table 3). These results indicate that driving speed variance increased after the first 30 minutes of driving. This result indicates that drivers were experiencing fatigue due to time-on-task (as anticipated), and that this fatigue resulted in poorer speed maintenance performance.

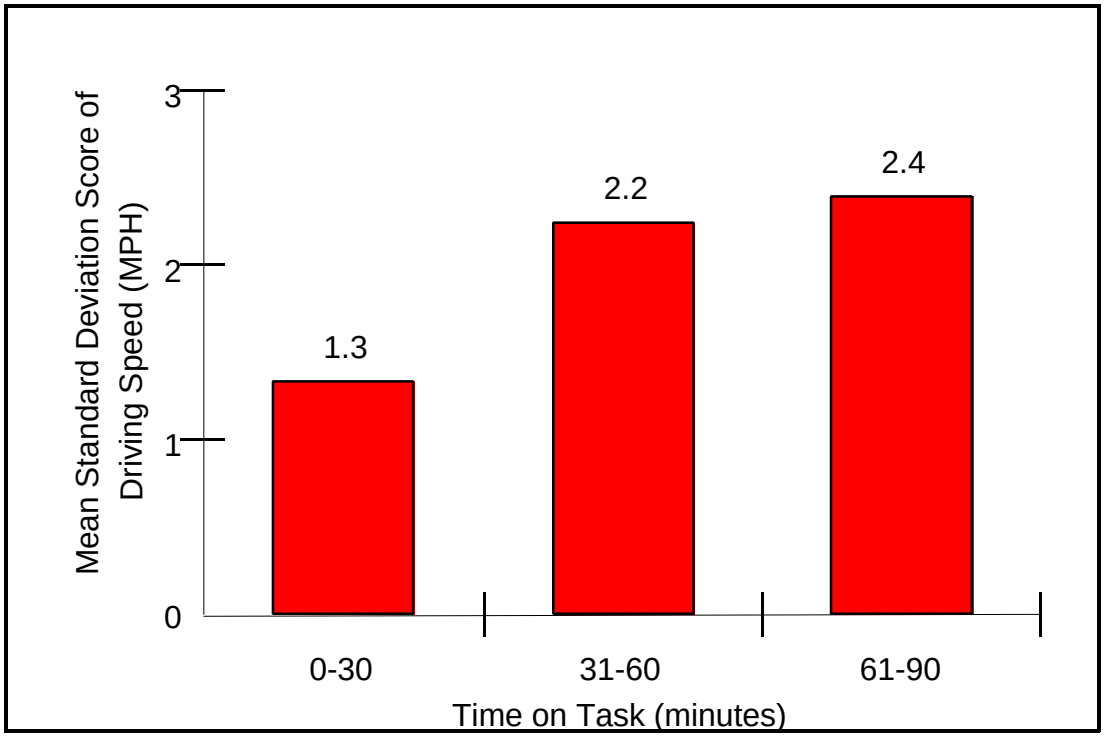


Figure 5. Effect of time-on-task on driving speed variability.

Longitudinal Acceleration

The MANOVA result for mean longitudinal acceleration (appendix A, table 4) indicated no significant difference across any of the independent variables. In addition, throttle and brake inputs, which are closely related to longitudinal acceleration, yielded no significance when they were analyzed separately.

The analysis for the standard deviation of longitudinal acceleration showed a three-way interaction effect for Time-On-Task x ATIS Complexity x Driving Load ($F(4,36) = 3.38$, $p<0.05$) and a main effect for Driving Load ($F(1,9) = 10.97$, $p<0.005$) (appendix A, table 4).

For the three-way interaction effect of Time-On-Task x ATIS Complexity x Driving Load, simple effect analyses of ATIS complexity and driving task load were conducted at each time-on-task condition. The result showed only a significant main effect of Driving Load, $F(1,9) = 12.9$, $p<0.005$ (appendix A, table 4), at the second 30-minute time-on-task condition. This indicates that subjects were having more difficulty driving during the second 30 minutes of the drive under high driving task load conditions. Perhaps at moderate fatigue levels, the differences in complexity are most pronounced, whereas when subjects are not fatigued, they do not have particular difficulty with roads of either complexity. Conversely, when subjects are very fatigued, they may have more difficulty driving in even the low driving load environment.

The significant main effect suggested that subjects adjusted their driving speed more abruptly under high driving load compared with the low driving load. Given the number and types of curves present, this finding is not surprising.

Lane Position Deviation

A three-way interaction effect between Sleep Deprivation, Time-On-Task, and ATIS Complexity, $F(4.36) = 3.95$ $p<0.005$ (appendix A, table 5), was significant for lane position standard deviation. To investigate the source of this interaction, two-way analyses of variance were conducted at each sleep-deprived condition. Figure 6 shows the result at the sleep-deprived condition. As shown: (1) the drivers showed increased lane deviation as time-on-task increased, $F(2,18) = 9.18$, $p<0.005$ (appendix A, table 6), and (2) the effect of ATIS complexity became apparent only at the last time-on-task condition, as indicated by Time-On-Task x ATIS Complexity interaction effect, $F(4,36) = 3.62$, $p<0.05$ (appendix A, table 6). In effect, pairwise t-tests (Fisher's least-significant difference test) showed significant differences only in the comparison of medium and low ATIS complexity at the last time-on-task condition, alpha = 0.05, df = 18, MSE = 0.078. In contrast, for the non-sleep-deprived condition, only a significant main effect of ATIS complexity was found, $F(2,18) = 15.82$, $p<0.001$ (appendix A, table 7). This result indicated that subjects in the non-sleep-deprived condition had more difficulty maintaining lane position when they were required to perform the most difficult ATIS task compared with the other two levels of ATIS complexity, alpha = 0.05, df = 18, MSE = 0.0243.

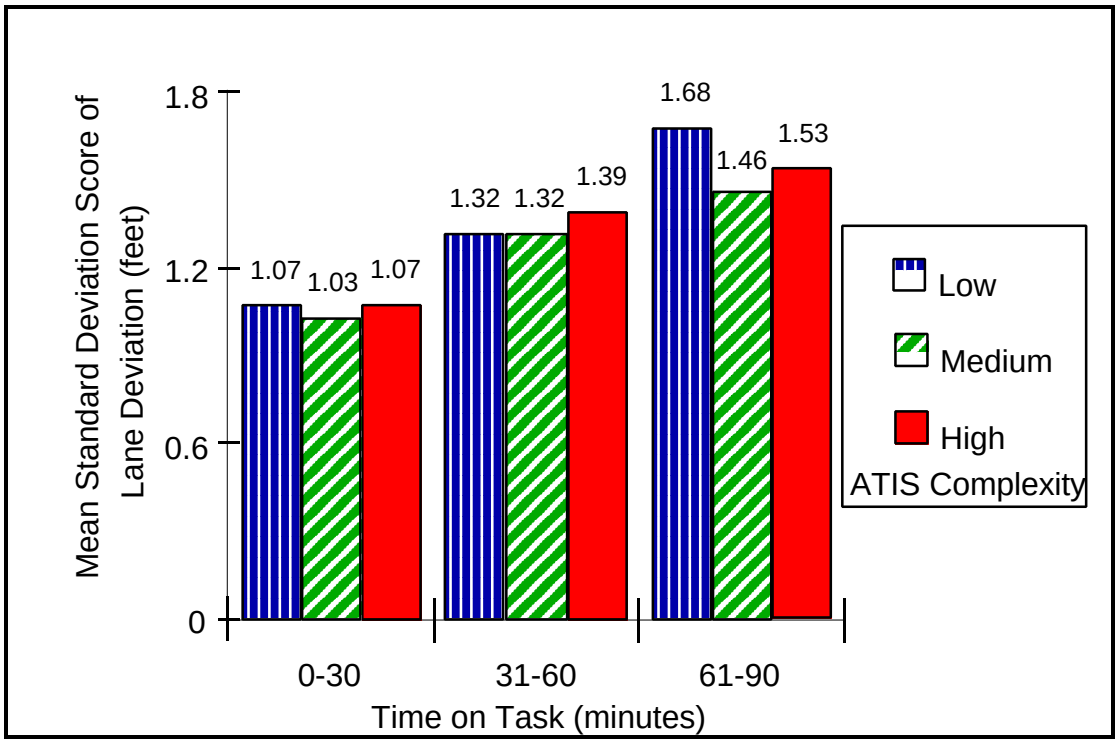


Figure 6. Relationship between time-on-task and ATIS complexity on the standard deviation ratings of lane deviation for the sleep-deprived condition.

Figure 7 shows that the difference between lane position standard deviation across the two sleep deprivation conditions was smallest at the most difficult ATIS complexity condition, and largest at the easiest ATIS complexity condition. This result is represented in the significant two-way interaction of Sleep Deprivation x ATIS Complexity, $F(2,18) = 5.72$, $p<0.05$ (appendix A, table 5). It appears that drivers maintained lane position most effectively when they had sufficient sleep. However, high ATIS complexity did not appear to adversely affect lane tracking performance in the sleep-deprived condition, relative to the other two ATIS complexity levels.

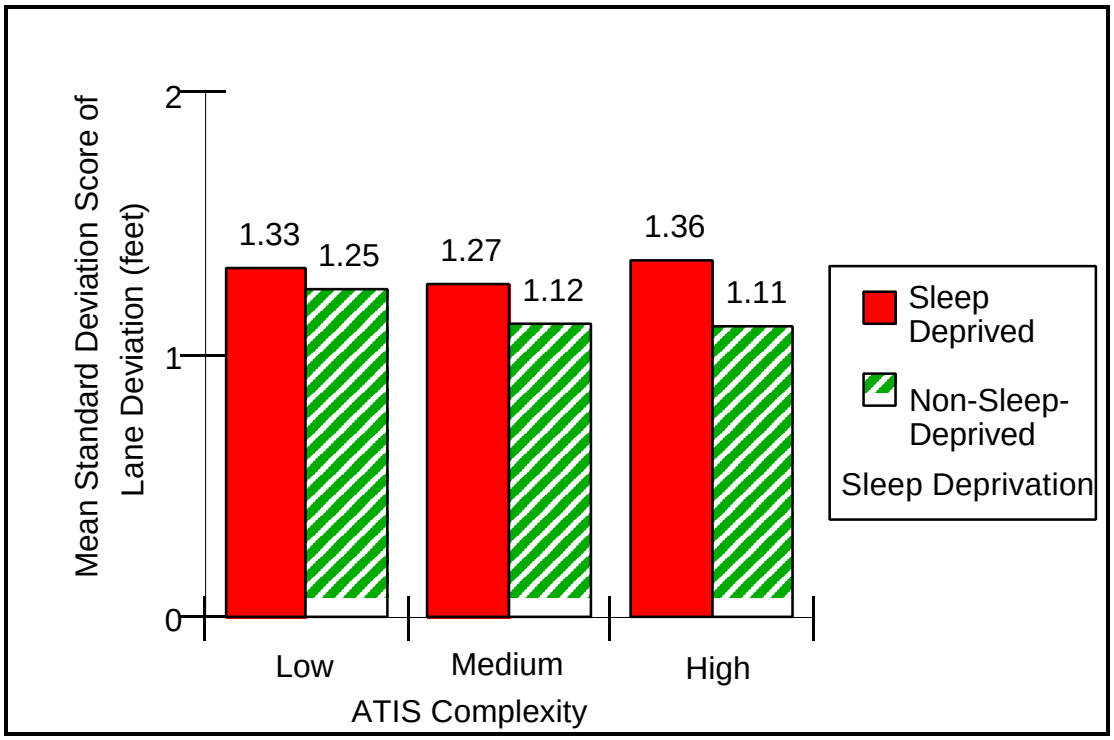


Figure 7. Relationship between sleep deprivation condition and ATIS task complexity on the standard deviation ratings of lane deviation.

As shown in figure 8, the mean standard deviation of lane position (deviation from the center of the lane) indicated that subjects showed greater lane deviation as time-on-task increased, $F(2,18) = 6.96$, $p<0.005$. When additional simple effect analyses for the time-on-task main effect were conducted at each level of this variable to examine the locus of the effect, significant differences were found in the comparison between the first time-on-task and the second time-on-task, and in the comparison between the first time-on-task and the third time-on-task, but not in the comparison between the second time-on-task and the third time-on-task. This result suggests that drivers suffered the greatest onset of fatigue between the first and second 30-minute sessions of the simulated drives.

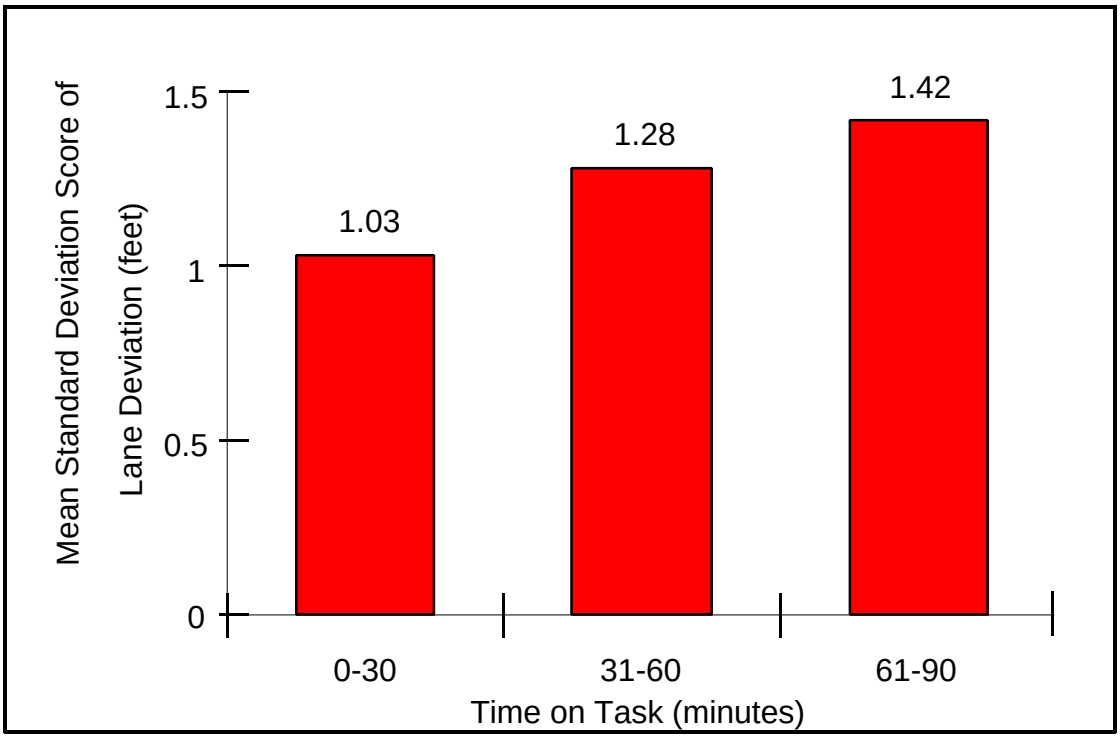


Figure 8. Effect of time-on-task on the standard deviations of lane deviation at the non-sleep-deprived condition.

In general, the results of lane deviations indicated that sleep-deprived subjects exposed to the last time-on-task condition (e.g., during a 60- to 90-minute driving period) showed decreased lane keeping performance when they were tested at the low level of ATIS complexity (note that no response was required in this condition). This result is apparently due to the relatively higher level of complexity, compensating for the effect of fatigue, whereas lane keeping performance declined in the lower ATIS complexity condition due to the effects of fatigue.

Lane Deviation Frequency

Although the lane was narrower and more curved in the high driving load condition than in the low driving load condition, the subjects crossed the center lane more frequently when they drove under the low driving load conditions compared with the high driving load conditions, $\chi^2(1) = 152.3$, $p<0.001$. The observed frequencies of lane deviations were 44 for the high driving load and 89 for the low driving load.

This result is of interest because, intuitively, one might expect drivers to cross the center lane more frequently when the road is tightly curved or narrower compared with the road being smoothly curved or wider. One possible explanation for this result is that the subjects may have paid more attention to the road in the high driving load condition (i.e., when the road was narrow and tightly curved) as compared with the low driving load condition (i.e., when the road was wide and smoothly curved). This interpretation can be supported by other indicators of driver performance. For example, as a result of paying more attention during the high driving load condition, drivers responded more slowly to high ATIS complexity conditions than the medium

ATIS complexity conditions in the high driving load condition compared with the low driving load condition. In addition, drivers reported higher levels of fatigue, as well as cognitive workload such as subjective time stress, visual effort, and psychological stress when they drove on the high driving load condition compared with the low driving load condition.

A second explanation for this finding is the presence or absence of traffic in the opposing lane. Dingus (1985) found that drivers deviate out of the lane more often when no traffic is present. Recall that the low driving load condition had less opposing traffic than the high driving load condition.

For these reasons, it seems more prudent to consider the two types of driving load conditions separately in describing the observed effect of sleep deprivation, time-on-task, and ATIS complexity on the frequency of lane deviation. The effect of sleep deprivation was significant only in the low driving load condition; drivers in the low driving load condition crossed the center lane more frequently when they were sleep-deprived than when they were not sleep-deprived, $\chi^2(1) = 4.89$, $p<0.05$. This result suggests that, although the drivers were fatigued due to sleep deprivation, they could maintain their vehicle as well as when they were not fatigued when driving in the high driving load condition. However, when driving in the low driving load condition, it appeared that the effect of sleep deprivation on the number of lane crossings became more pronounced, resulting in more errors in the sleep-deprived condition vs. the non-sleep-deprived condition.

In contrast to the effect of sleep deprivation, the significant effect of fatigue due to time-on-task was observed in both driving load conditions. As shown in figure 9, drivers crossed the center lane more frequently as the time-on-task increased both in the high driving load condition, $\chi^2(2) = 35.91$, $p<0.001$, and in the low driving load condition, $\chi^2(2) = 74.96$, $p<0.001$. In particular, a notable increase in the number of lane deviations was shown after the first 30 minutes of driving. For example, in the high driving load condition, subjects rarely crossed the center lane in the first time-on-task condition (1.8 times on average in 30 minutes of driving). However, after this period of time, subjects made errors more frequently (e.g., 32 times in the second time-on-task condition, and 38 times in the last time-on-task condition). This pattern can also be observed in the low driving load condition, but with higher frequency of lane crossings than the complex driving load. In addition, note the relatively small increase in the number of lane crossings after the second time-on-task condition for both driving loads. It is evident from these data that the effects of fatigue generally became apparent after the first 30 minutes of driving and that drivers remained in a somewhat moderately fatigued state for the remainder of the drive.

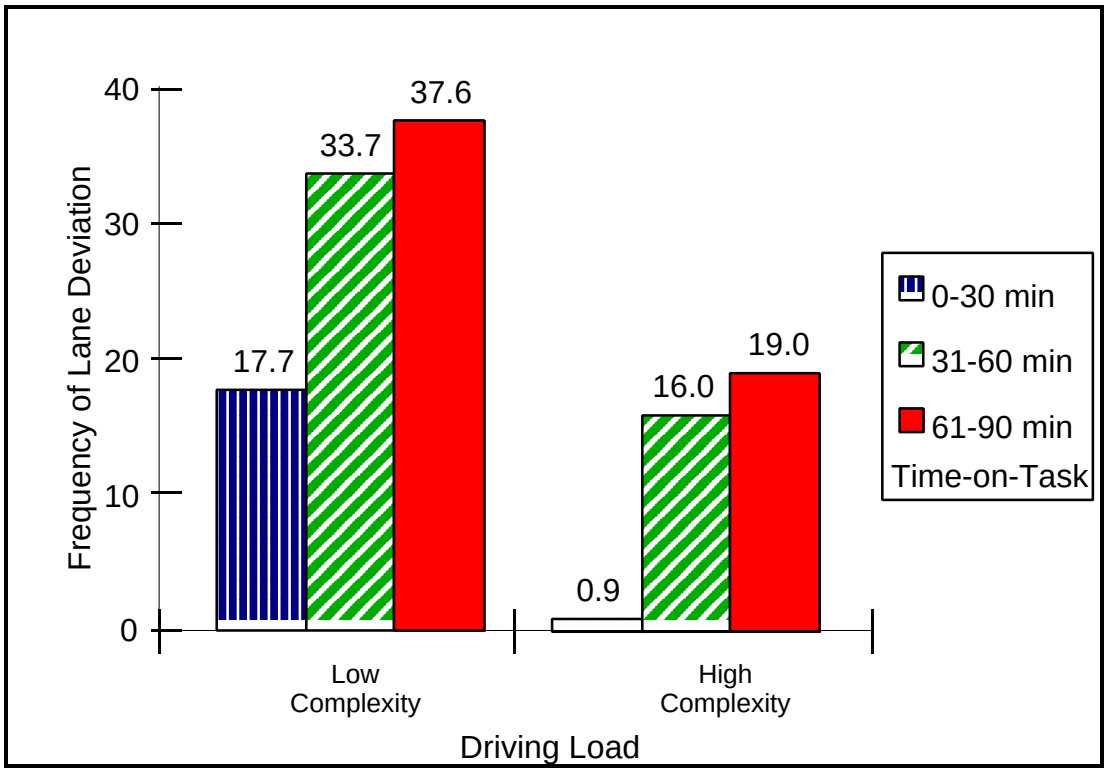


Figure 9. Relationship between time-on-task and driving load on the number of lane deviations.

As discussed previously, if the subjects paid more attention to the road in the high driving load condition to maintain their vehicle properly, it would follow that the effect of different levels of ATIS complexity on the number of lane crossings would be more pronounced in the high driving load condition than in the low driving load condition. For example, more lane deviations would be expected when subjects were asked to perform a more difficult ATIS task (where scanning of the ATIS, decision making, and button pressing were required) than relatively easier task requirements. However, the results showed that the effect of ATIS complexity on the number of lane deviations was significant only in the low driving load condition, $\chi^2(2) = 28.75$, $p<0.001$. This indicated that drivers made more frequent lane deviations when performing difficult ATIS tasks compared with ATIS tasks of lower complexity. In particular, in the low driving load condition, the number of lane crossings did not differ in the medium and the low ATIS complexity conditions (see figure 10). This finding may be attributed to the lowering of lane keeping standards by drivers under high ATIS complexity in the absence of other traffic. That is, a driver can deviate to some extent into the oncoming lane when no traffic is present. As such, it is possible that drivers may have let their vehicle "drift" while performing the high ATIS complexity tasks knowing that no oncoming traffic was approaching. This result has been shown in other ATIS-related field studies (e.g., Antin et al., 1990), and has been shown to not necessarily affect overall driving safety.

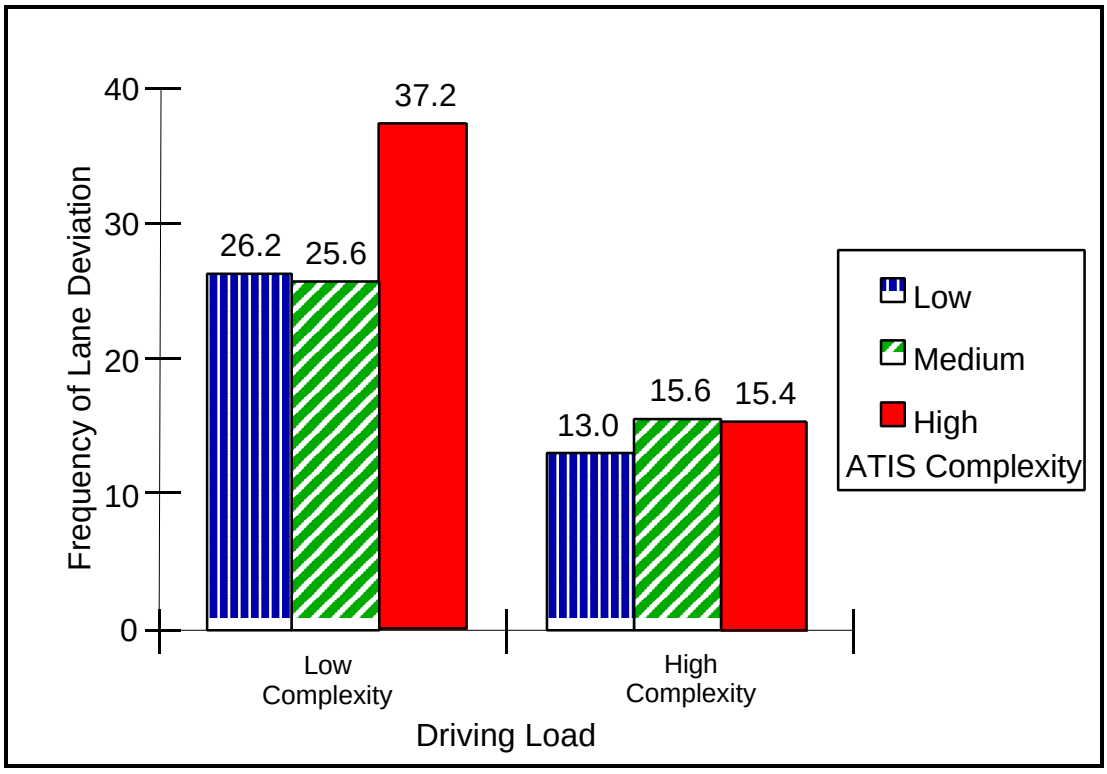


Figure 10. Relationship between ATIS complexity and driving load on the number of lane deviations.

ATIS TASK PERFORMANCE

Response Latency

A MANOVA with five independent variables (sleep condition, time-on-task, ATIS complexity, driving load, and ATIS information modality—visual or auditory) was conducted for response latency. Recall that one-half of the warning stimuli were presented via the auditory modality, and one-half were presented via the visual modality. Thus, the modality independent variable could be analyzed for this dependent measure.

Two-way interaction effects of Time-On-Task x ATIS Information Modality, $F(2,18) = 5.33$, $p<0.05$, ATIS Complexity x Driving Load, $F(1,9) = 7.03$, $p<0.05$, and ATIS Complexity x ATIS Information Modality, $F(1,9) = 16.39$, $p<0.01$, were significant (appendix A, table 8). The interaction effects of Time-On-Task x ATIS Information Modality indicate that an increase in response latency due to time-on-task was greater in the visual modality than in the auditory modality (see figure 11). This finding may indicate that as drivers became more fatigued, their visual scanning/attention pattern changed such that they concentrated more on the roadway and less on the visual display.

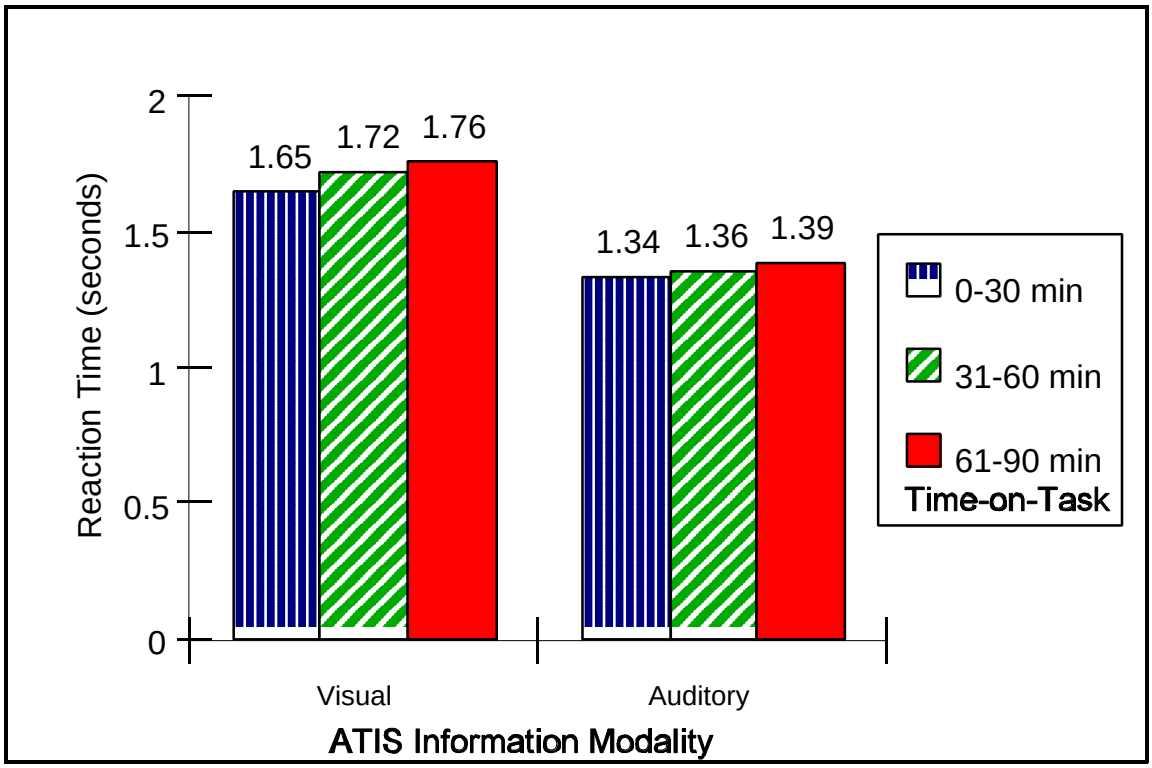


Figure 11. Relationship between time-on-task and ATIS information modalities on response latency in the ATIS task.

The interaction effect of ATIS Complexity x Driving Load was due to the fact that the response latency was slightly greater during high driving load when the ATIS complexity was also high relative to the medium ATIS complexity. In contrast, there was no difference in response latency between ATIS complexity conditions in the low driving load condition (figure 12). This finding was likely due to the increased workload that the driver was experiencing in the complex ATIS/high driving load condition. Recall that the secondary tasks were not present in the lowest level of ATIS complexity because it was felt that the presence of these secondary tasks would raise the ATIS complexity beyond the level operationally defined as "low." Similarly, the ATIS Complexity x ATIS Information Modality interaction was due to a larger difference in response latency between high and medium levels of ATIS complexity in the auditory modality (1.38 s vs. 1.32 s) than in the visual modality (1.71 s vs. 1.72 s) (figure 13). The magnitude of the differences, although significant, is probably not particularly meaningful in the overall assessment of the ATIS.

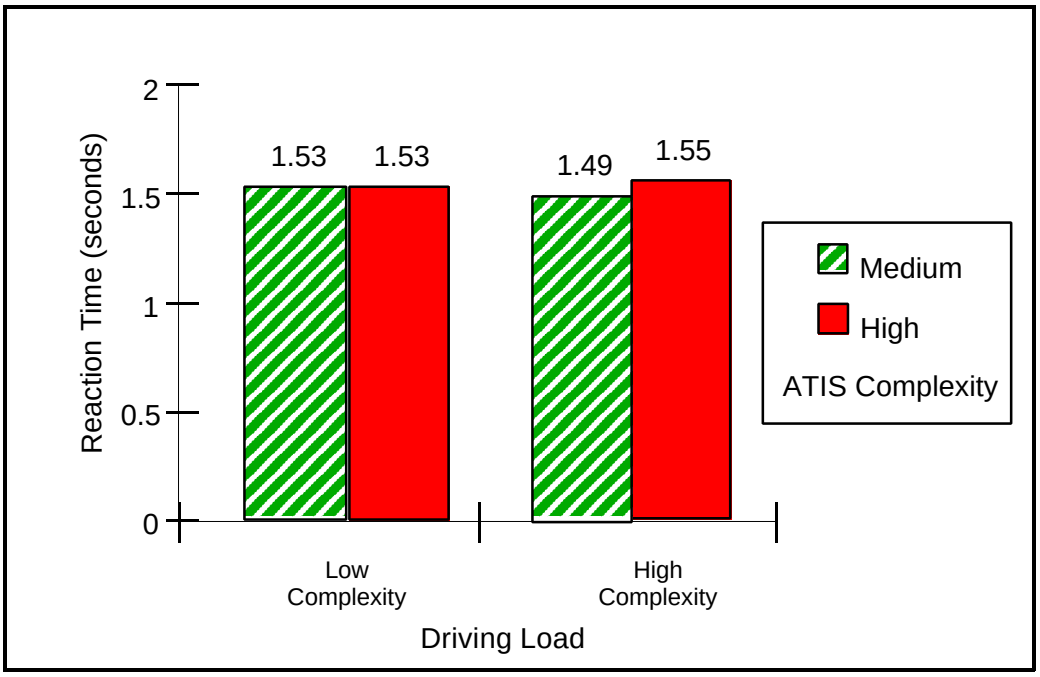


Figure 12. Relationship between ATIS complexity and driving load on response latency for the ATIS task.

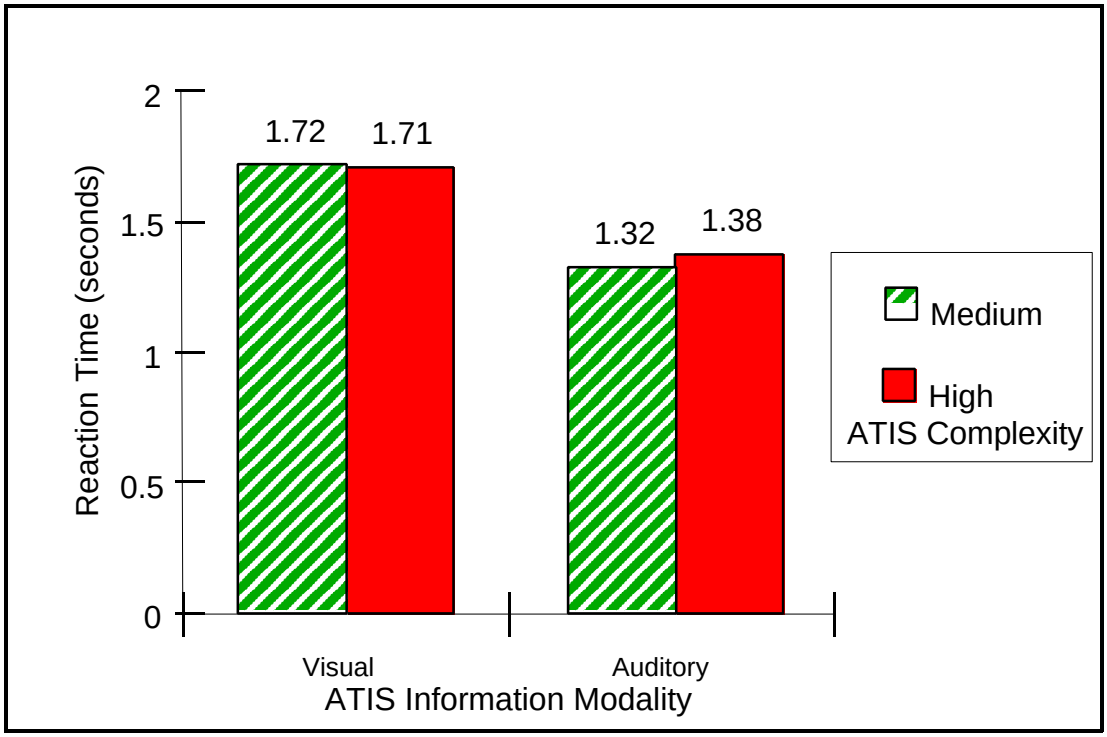


Figure 13. Relationship between ATIS complexity and ATIS information modality on response latency in the ATIS task.

The main effect of ATIS information modality was significant, $F(1,9) = 34.66$, $p<0.001$ (appendix A, table 8), indicating that subjects responded significantly faster when auditory ATIS information was presented (1.36 s) than when visual ATIS information was presented (1.71 s). This benefit in response latency is expected given the omnipresence of auditory stimuli.

Error Frequency

As mentioned previously, error responses in the ATIS task occurred when subjects made very slow responses or wrong button selections. The Chi Square analysis for this measure indicated that drivers made more errors in the high ATIS complexity condition than in the medium ATIS complexity condition (note that no response was required in the low ATIS complexity condition), $\chi^2(1) = 8.53$, $p<0.01$, and in the earlier time-on-task condition, $\chi^2(2) = 16.13$, $p<0.001$.

The increase in number of errors is likely due to the increase in information complexity in the high driving load condition. The increased frequency of errors in the earlier time-on-task condition is somewhat counter-intuitive, as the level of fatigue and mental effort increased as time-on-task increased. One explanation is a practice effect leading to an error reduction later in the drive. Note, however, that subjects practiced the tasks until error-free response was exhibited prior to the drive. Thus, an apparent practice effect was somewhat surprising.

FATIGUE ASSESSMENT

Slow Eye Closure Measurement

Frequency of Complete Eye Closure

When the number of complete eye closures (e.g., when the eye lid covered 99.5 percent of the eyes) was analyzed, the results indicated that drivers closed their eyes more frequently when they were tested in the sleep-deprived condition than in the non-sleep-deprived condition, $\chi^2(1) = 19.78$, $p<0.001$. For example, drivers closed their eyes about 28 times within 90 minutes of driving when sleep-deprived, whereas they closed their eyes 19 times when not sleep-deprived.

In addition, the frequency of the complete eye closure was significantly different depending on the time-on-task; as time-on-task increased, subjects showed more frequent complete eye closures, $\chi^2(2) = 25.39$, $p<0.001$ (figure 14). In particular, the effect of time-on-task on the number of complete eye closures was higher during the last 30 minutes of driving than the first two time-on-task conditions. The number of complete eye closures did not significantly differ when compared across the ATIS complexity conditions or driving load conditions, suggesting that complete eye closure is more significantly affected by level of fatigue rather than by level of driving load or ATIS complexity.

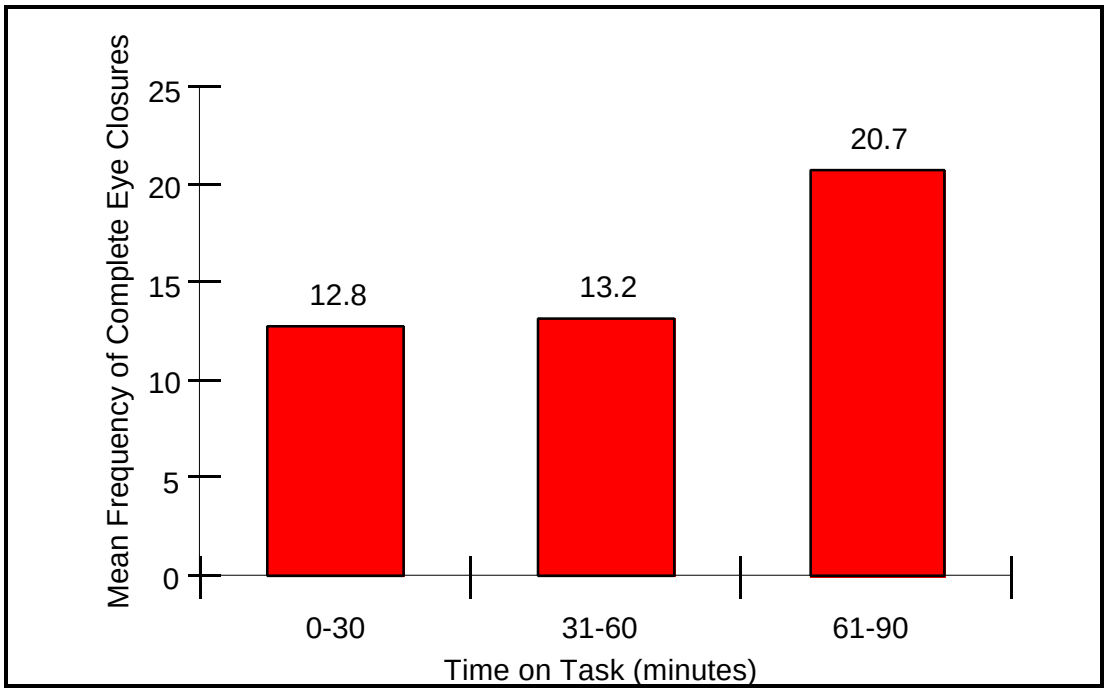


Figure 14. Effect of time-on-task condition on the number of complete eye closures.

Mean Eye Lid Position

The four-way interaction effect of Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load was significant, $F(6, 54) = 2.69$, $p<0.05$ (appendix A, table 9). Additional simple effect analyses for this interaction effect were conducted at each sleep deprivation condition. The results revealed a significant main effect of time-on-task at the non-sleep-deprived condition, $F(2,18) = 6.71$, $p<0.01$ (appendix A, table 10), but not at the sleep-deprived condition, $p>0.05$ (appendix A, table 11). This indicates that eye lid closure significantly increased as time-on-task increased only when subjects had enough sleep the night prior to the experiment. In addition, the interaction effect of Time-On-Task x ATIS Complexity was significant for sleep condition, $F(4,36) = 3.37$, $p<0.05$ (appendix A, table 10) (see figure 15). It is interesting to note that the ATIS task had somewhat of an arousing affect as evidenced by the last 30 minutes of the drive (figure 15), counteracting the fatigue effects due to time-on-task.

Two main effects were also significant for mean eye ramp position. Drivers' eye ramps were significantly lower in the sleep-deprived condition (29.1 percent closed) as opposed to the non-sleep-deprived condition (20.58 percent closed), $F(1,9) = 13.15$, $p<0.01$ (appendix A, table 9). Also, drivers' eye ramps were significantly lower as time-on-task increased (20.86 percent for 0-30 minutes, 25.44 percent for 31-60 minutes, and 28.21 percent for 61-90 minutes), $F(2,18) = 5.37$, $p<0.05$ (appendix A, table 9).

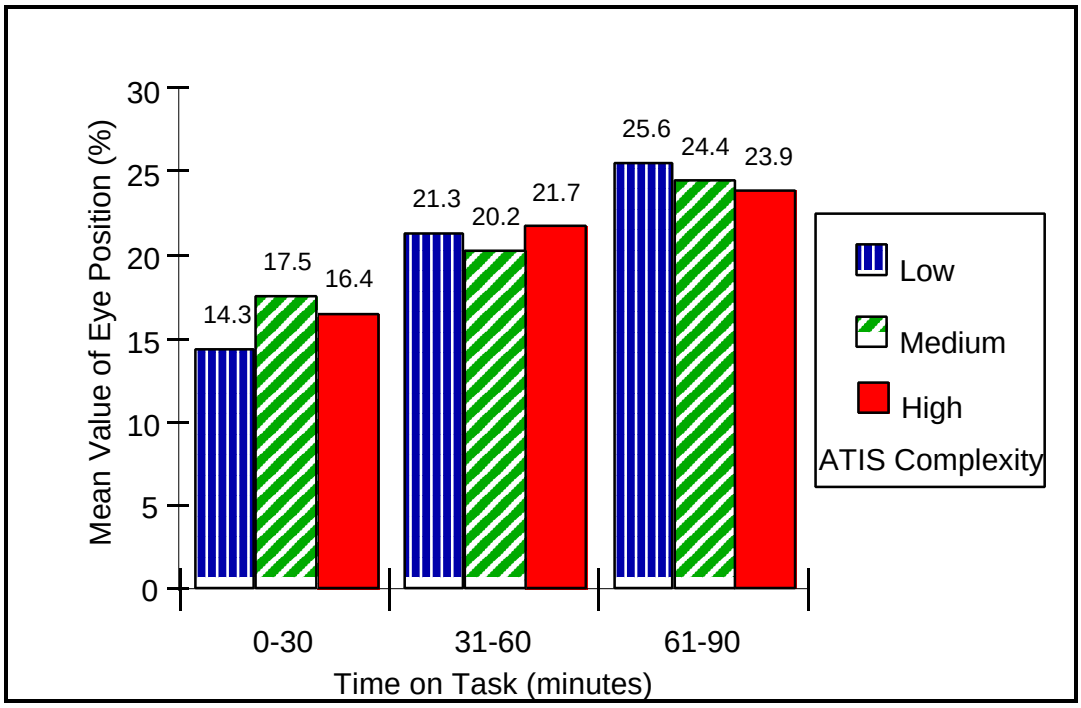


Figure 15. Relationship between ATIS complexity and time-on-task condition on the mean eye ramp position.

This pattern of results suggests that when subjects were deprived of their sleep, the portion of eye ramp covered during driving was significantly higher than when they had enough sleep before the experiment, and did not change significantly as time-on-task increased (i.e., the portion of the eye lid covered had already reached the maximum level in which the subject could still drive even at the earliest part of the time-on-task). In contrast, when subjects were not deprived of their sleep, the effect of time-on-task was significant.

Percentage of Eye Ramp Closure Time

Similar to the results of mean eye lid position and the frequency of complete eye closures, the percentage of eye ramp closure time was significantly higher for the sleep-deprived condition (2.8 percent) than the non-sleep-deprived condition (1.19 percent) closure time), $F(1,9) = 15.21$, $p<0.01$ (appendix A, table 12). No other significant result was found.

Subjective Fatigue Rating

Fatigue Levels Before and After the Experiment

As described earlier, a subjective fatigue rating scale (revised from Yoshitake, 1971), consisting of a multi-item questionnaire to measure various dimensions of fatigue (drowsiness and dullness, difficulty in concentration, and projection of physical impairment) was administered during the study. It was used two times, once before and once after the experiment. For both times, subjects were seated at a desk and asked to fill out the questionnaire. Subjective fatigue scores were

calculated by dividing the number of "yes" answers by total number of items in each dimension, and converted to percentage scores for later analysis. Therefore, the higher percentage of "yes" responses indicated that subjects felt a higher level of fatigue. These fatigue rating scales are provided in appendix C.

By adopting this measurement, the following can be explored: (1) whether sleep deprivation made any difference in the level of subjective fatigue "before" the experiment—i.e., did the manipulation of sleep deprivation as described above relate to the subjects' level of fatigue, and (2) whether there is any change in magnitude of subjective fatigue level in each fatigue dimension after the experiment.

To answer the first question, a t-test on the subjective fatigue ratings reported before the experiment were compared for sleep-deprived and non-sleep-deprived conditions. The results showed that subjects felt more drowsiness (see pre-test condition at figure 16) and difficulty in concentration (pre-test condition at figure 17) when they were sleep-deprived before the experiment, $t(18) = 6.88$, $p<0.001$, and $t(18) = 2.33$, $p<0.05$, respectively, than when they had slept. There was no significant difference in the physical impairment (pre-test condition, figure 18) dimension between the two sleep deprivation conditions, $t(18) = 1.41$, $p>0.05$.

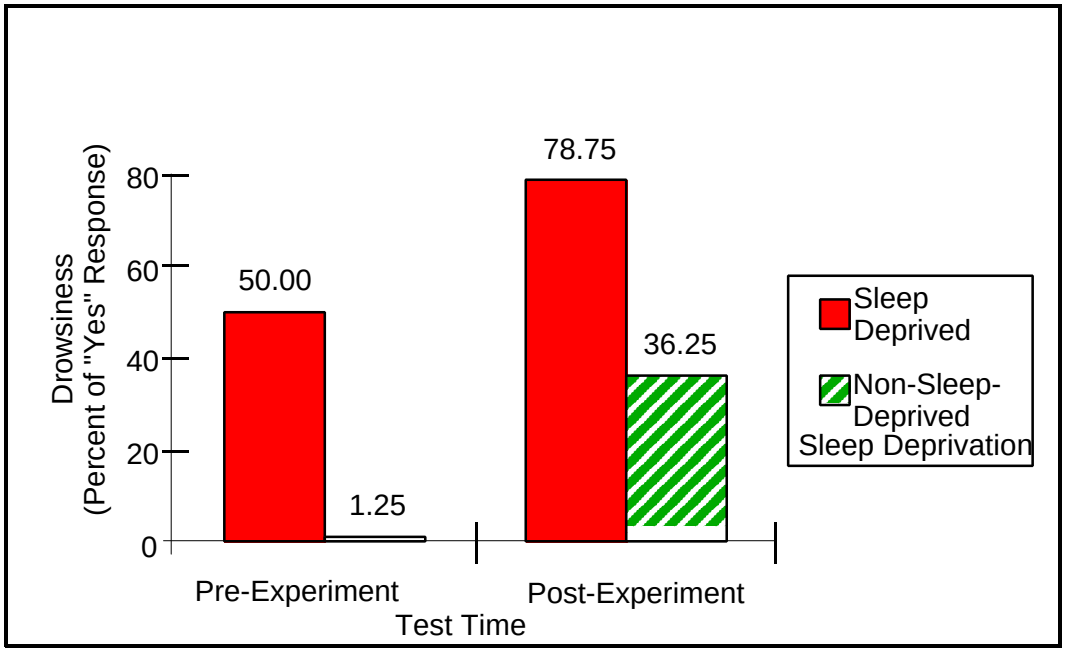


Figure 16. Effect of sleep deprivation on subjective rating on drowsiness when measured before and after the experiment.

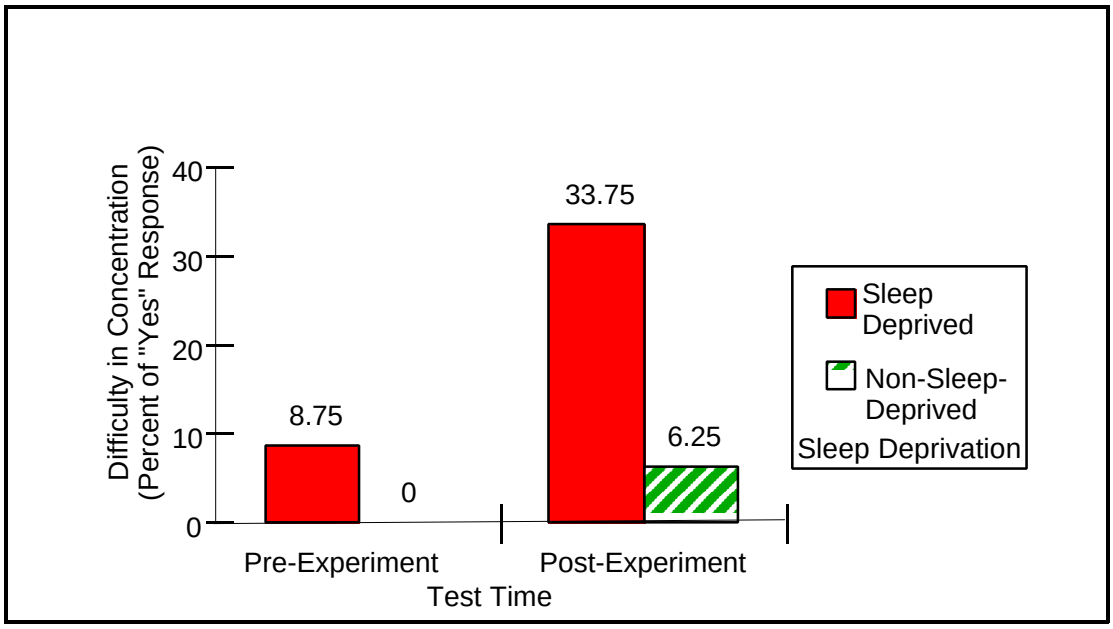


Figure 17. Effect of sleep deprivation on subjective rating on difficulty in concentration when measured before and after the experiment.

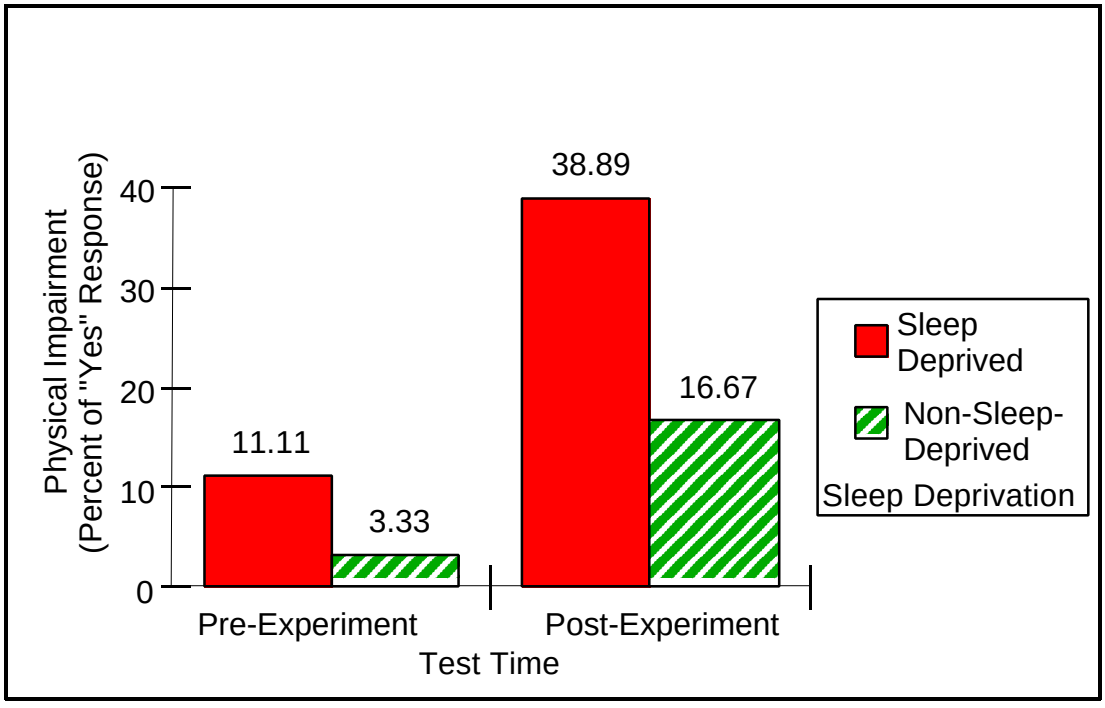


Figure 18. Effect of sleep deprivation on subjective rating on physical impairment when measured before and after the experiment.

When the same comparisons were made based on the scores reported "after" the experiment, the effect of sleep deprivation revealed significant differences in all dimensions $t(18) = 4.81$, $p<0.001$ for drowsiness, $t(18) = 2.17$, $p<0.05$ for difficulty in concentration, and $t(18) = 2.43$, $p<0.05$ for physical impairment. To summarize, the results of the comparison of the effect of sleep deprivation on the subjective fatigue rating before and after the experiment were: (1) sleep-deprived subjects felt more drowsy and they had more difficulty concentrating and greater physical impairment before the experiment, and (2) 90 minutes of driving exaggerated the effect of sleep deprivation on the difference in magnitude of subjective fatigue.

Another important question relating to the effect of sleep deprivation on the subjective fatigue ratings is whether the magnitude of subjective fatigue in the same sleep deprivation condition changed due to the experience of 90 minutes of driving. To answer this question, the pre- and post-experimental subjective fatigue ratings of the same sleep deprivation condition were compared in a t-test. The result showed that subjects in the non-sleep-deprived condition felt more drowsiness (1.25 percent vs. 36.25 percent) after the experiment, $t(18) = 6.68$, $p<0.001$, but no difference in difficulty in concentration or physical impairment. In contrast, those in the sleep-deprived condition felt not only more drowsiness (50 percent vs. 78.75 percent), $t(18) = 2.86$, $p<0.05$, but also more physical impairment (11.11 percent vs. 38.89 percent), $t(18) = 3.27$, $p<0.01$. Interestingly, difficulty in concentration did not reveal any significant difference before and after the experiment for both sleep deprivation conditions. These results suggest that: (1) subjects felt more fatigued after the experiment when they were tested in the sleep-deprived condition relative to the non-sleep-deprived condition, and (2) subjects had no significant difficulty in concentrating on performing given tasks regardless of sleep deprivation condition.

Subjective Fatigue Rating at Each Experimental Condition

As the above-mentioned multi-dimensional fatigue scale was used only before and after the experiment, the effects of ATIS complexity, driving load, and time-on-task on subjective fatigue level could only be explored by adopting another type of fatigue scale. This instrument used a uni-dimensional seven-point rating scale (Pearson & Bayer, 1956), and was employed at the end of each experimental condition. The numbers (one to seven) were assigned to the different descriptions (statements) according to various levels of fatigue, and subjects were trained to match each number to the statement before the start of the experiment. Subjects were asked to report verbally the number of the statement that described their level of fatigue, and the experimenter recorded the response.

The MANOVA result for this measurement indicated that subjects rated their fatigue level higher when they were tested under the sleep-deprived condition compared with the non-sleep-deprived condition (5.2 vs. 3.3), $F(1,9) = 22.25$, $p<0.001$ (appendix A, table 13). Also, main effects of time-on-task (figure 19), $F(2,18) = 29.86$, $p<0.001$, and driving load (figure 20), $F(1,9) = 5.62$, $p<0.05$, were found. Note that a simple effect analysis of the time-on-task main effect showed that only the comparison of the difference between the first 30 minutes and the last 30 minutes was significant, $t(18) = 2.92$, $p<0.01$. No other main effect or interaction effects were significant.

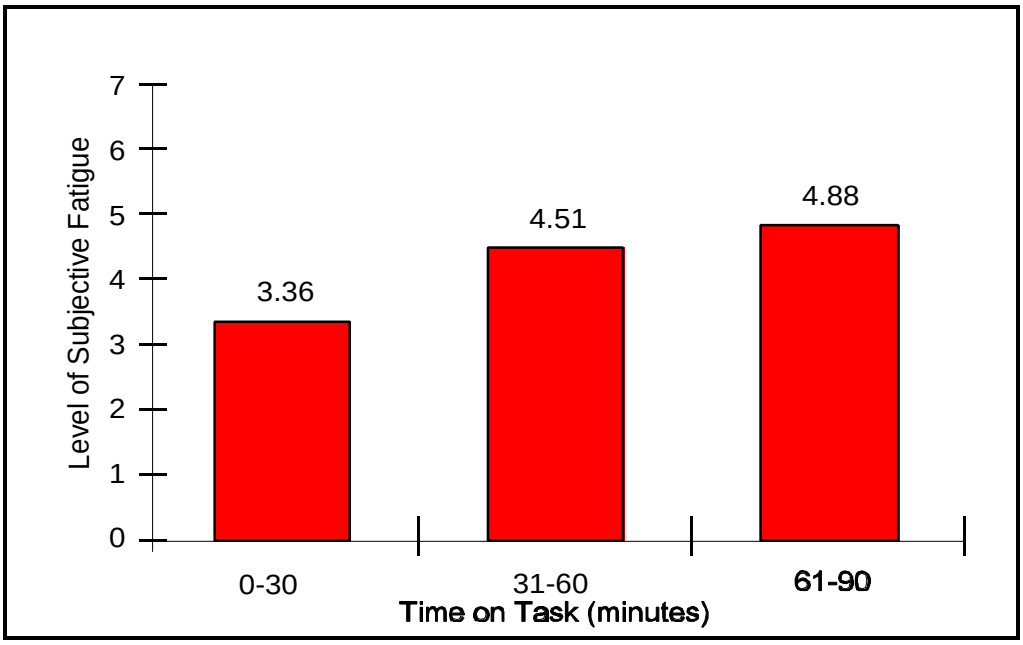


Figure 19. Effect of time-on-task condition on the level of subjective fatigue when measured during the experiment.

WORKLOAD ASSESSMENT

Time Stress

MANOVA results for subjective time stress rating in the SWAT revealed a three-way interaction effect of Time-On-Task x ATIS Complexity x Driving Load was significant, $F(4,36) = 3.18$, $p<0.05$ (appendix A, table 14). Simple effect analyses for this interaction were conducted at each time-on-task condition. Figure 20 shows that the main effect of ATIS complexity was significant in all time-on-task conditions; the first 30-minute time-on-task condition, $F(2,18) = 5.85$, $p<0.05$ (appendix A, table 15), the second 30-minute time-on-task condition, $F(2,18) = 5.93$, $p<0.05$ (appendix A, table 16), and the last 30-minute time-on-task condition, $F(2,18) = 5.42$, $p<0.05$ (appendix A, table 17). As shown by the figure, time stress was generally rated higher for the medium ATIS complexity condition under the higher driving load condition during the last 60 minutes of the drive. Based on some of the previous fatigue results, it is apparent that the combined stressors of fatigue and workload were causing the subjects to feel more time stress.

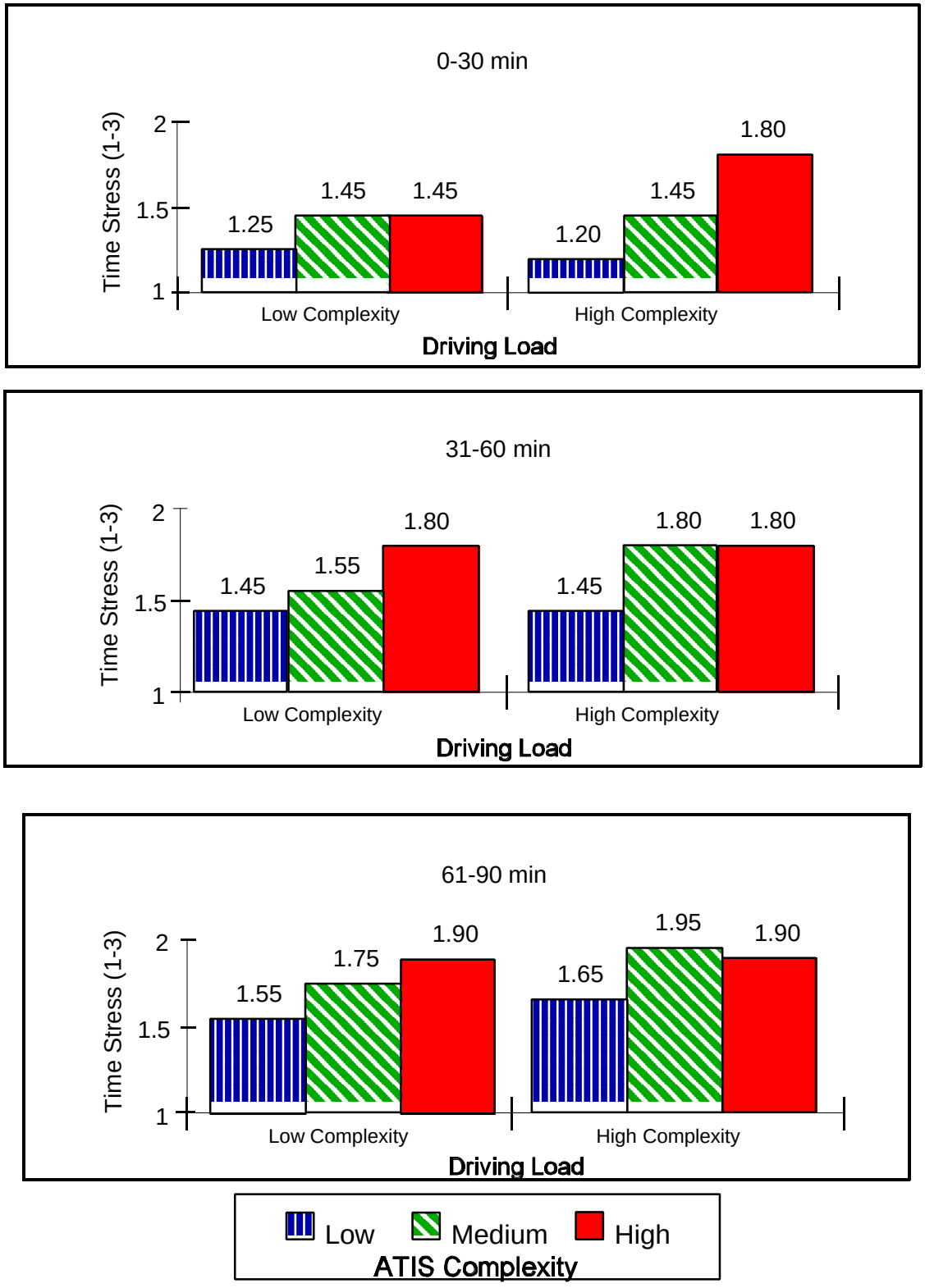


Figure 20. Relationship of time stress rating between ATIS complexity and driving load at each time-on-task condition.

Several main effects were also significant for time stress. Subjects reported higher time stress under the sleep-deprived condition compared with the non-sleep-deprived condition, $F(1,9) = 6.51$, $p<0.05$, as time-on-task increased, $F(2,18) = 9.41$, $p<0.01$, as ATIS complexity increased, $F(2,18) = 8.65$, $p<0.01$, and in the high driving load condition vs. the low driving load condition, $F(1,9) = 10.79$, $p<0.05$ (appendix A, table 14).

Visual Effort

MANOVA results for subjective visual effort rating in the SWAT showed that drivers reported a higher visual effort level when they were tested under the sleep-deprived condition than under the non-sleep-deprived condition, $F(1,9) = 5.50$, $p<0.05$, as time-on-task increased, $F(2,18) = 7.24$, $p<0.01$, as ATIS complexity increased, $F(2,18) = 13.79$, $p<0.001$, and in the high driving load condition, $F(1,9) = 9.77$, $p<0.05$ (appendix A, table 18). No interaction effect was significant.

Psychological Stress

The MANOVA results for drivers' psychological stress rating showed that a three-way interaction effect of Time-On-Task x ATIS Complexity x Driving Load was significant, $F(4,36) = 2.71$, $p<0.05$ (appendix A, table 19). The simple effect analysis for this interaction conducted at each time-on-task condition showed that the main effect of ATIS complexity was significant in the first time-on-task condition, $F(2,18) = 6.38$, $p<0.05$ (appendix A, table 20), but not in the second time-on-task condition (appendix A, table 21), or the third time-on-task condition (appendix A, table 22). The main effect of driving load was only significant in the second 30-minute time-on-task condition (figure 21). No interaction effect was significant.

Significant main effects resulted for the sleep-deprived condition, $F(1,9) = 10.94$, $p<0.005$, time-on-task, $F(2,18) = 6.95$, $p<0.01$, ATIS complexity, $F(2,18) = 5.24$, $p<0.05$, and driving load, $F(1,9) = 8.68$, $p<0.05$ (appendix A, table 19). All main effect findings were in the directions expected.

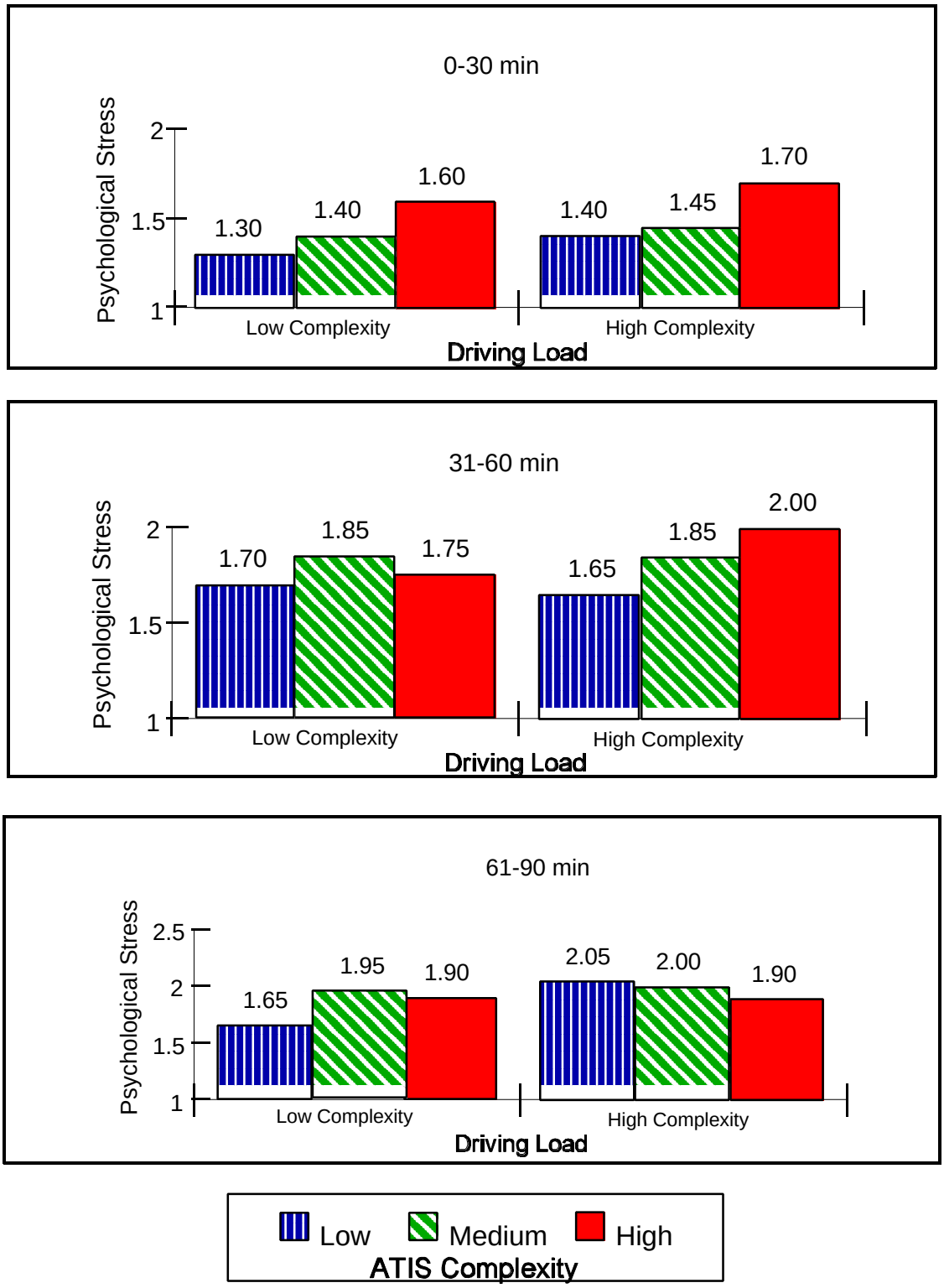


Figure 21. Relationship of psychological stress rating between ATIS complexity and driving load at each time-on-task condition.

These results suggest that although sleep deprivation, ATIS complexity, and driving load affected subjects' "general" rating level on psychological stress—i.e., the magnitude of subjective psychological stress increased with fatigue, as the ATIS complexity increases, and as driving loads became complex—this pattern of response should be considered in terms of elapsed experimental time (e.g., time-on-task). For example, ATIS complexity affected ratings only in the first 30 minutes of driving, and driving loads only in the second 30 minutes of driving. In the last 30 minutes of driving, these variables (ATIS complexity and driving load) had no effect on drivers' psychological stress level.

CHAPTER 4: GENERAL CONCLUSIONS

The purpose of the present study was to investigate the combined effect of truck driver fatigue and mental workload on driving performance and other behavior during interaction with complex in-vehicle information systems, specifically ATIS. Sleep deprivation and time-on-task were used to manipulate different levels of fatigue, whereas ATIS complexity and driving load were used to induce different levels of mental workload. Driving performance, eye ramp movement, ATIS task performance, and subjective ratings were measured to determine the effect of fatigue and mental workload. Basic hypotheses were: (1) if ATIS increases arousal and reduces fatigue, then drivers would experience no degradation in driving performance and other behavioral indices, and (2) in contrast, if ATIS overloads the driver, driving performance and other behavioral indices would be decreased under circumstances of fatigue.

Both sleep deprivation and increased time-on-task induced driver fatigue. In terms of ATIS task performance, sleep deprivation had no discernable impact. That is, although drivers were fatigued due to lack of sleep, responses to ATIS tasks were similar regardless of the level of sleep deprivation. This result is important for ATIS designers and suggests that interaction with an ATIS is not detrimental to driving performance under fatiguing conditions. In fact, some results suggest that interaction with an ATIS may aid fatigued drivers.

For mental workload, increasing the driving load had a significant impact on driving performance. Roads that were narrower and had tighter curves induced greater deviation for longitudinal acceleration, steering wheel angle inputs, and lateral acceleration. In addition, drivers' subjective ratings indicated greater mental workload for the high driving load condition. In addition, higher rated mental workload scores for higher ATIS complexity were also found. These results have implications for the timing of ATIS messages. That is, message onset that occurs when the driver is in a high driving load environment may be more difficult to process compared with the same message being presented in a low driving load environment.

The most common types of ATIS displays will use visual and auditory modalities to display information. Past research has shown the benefits of using auditory messages for ATIS (Labiale, 1990; Parkes, Ashby, and Fairclough, 1991; Streeter and Vitello, 1986; McKnight and McKnight, 1992). Not surprisingly, in the present study, drivers generally showed faster response times when they were provided with auditory information compared with visual information. However, caution must be used when generalizing this result since information modality interacted with ATIS complexity. That is, it was found that the increase in the reaction time for the auditory modality was greater than the visual modality when the complexity of ATIS information increased (e.g., from medium to high). This finding suggests that information-overloading in the auditory channel had a greater performance effect than in the visual channel.

Based on the results of this experiment, the following guidelines are recommended:

- Fatigue-related driving performance effects can be mitigated to some extent when drivers interact with an ATIS. Therefore, drivers should not be discouraged from ATIS interaction under fatiguing conditions (for example, see figure 15).
- It appears that commercial drivers will be able to respond to safety-related ATIS

information, as well as maintain general ATIS task performance, while moderately fatigued (see figure 11).

- Other research has shown that increasing ATIS complexity can increase mental workload, thus decreasing driving performance. However, commercial drivers are able to operate ATIS systems of moderate complexity with no apparent degradation in performance (for example, see figure 7).
- If practical, presentation of ATIS messages should occur when driving task demands are minimal. Particularly in the case of CVO, some messages could be filtered and sequenced to aid commercial drivers by leveling task demands.

APPENDIX A

Table 2. Multivariate analysis of variance for mean value of driving speed.

Source	df	S	MS	F	p
Sleep Deprivation	1	13258.7200	13259	2.1600	〉0.05
Sleep Deprivation x Subjects	9	55190.3500	6132		
Time-On-Task	2	17365.1200	8683	2.3900	〉0.05
Time-On-Task x Subjects	18	65424.2000	3635		
ATIS Complexity	2	375.0300	188	0.4000	〉0.05
ATIS Complexity x Subjects	18	8423.4500	468		
Driving Load	1	1136.8600	1137	1.1700	〉0.05
Driving Load x Subjects	9	8776.9500	975		
Sleep Deprivation x Time-On-Task	2	4400.0300	2200	0.4400	〉0.05
Sleep Deprivation x Time-On-Task x Subjects	18	89922.7000	4996		
Sleep Deprivation x ATIS Complexity	2	157.0300	79	0.4800	〉0.05
Sleep Deprivation x ATIS Complexity x Subjects	18	2937.2000	163		
Sleep Deprivation x Driving Load	1	941.9600	942	0.4000	〉0.05
Sleep Deprivation x Driving Load x Subjects	9	21198.9400	2355		
Time-On-Task x ATIS Complexity	4	309.8000	77	0.1000	〉0.05
Time-On-Task x ATIS Complexity x Subjects	36	28899.0700	803		
Time-On-Task x Driving Load	2	1357.8900	679	1.1800	〉0.05
Time-On-Task x Driving Load x Subjects	18	10317.2800	573		
ATIS Complexity x Driving Load	2	976.5200	488	1.4100	〉0.05
ATIS Complexity x Driving Load x Subjects	18	6240.0600	347		
Sleep Deprivation x Time-On-Task x ATIS Complexity	4	796.2200	199	0.6400	〉0.05
Sleep Deprivation x Time-On-Task x ATIS Complexity x Subjects	36	11116.0000	309		
Sleep Deprivation x Time-On-Task x Driving Load	2	755.1100	378	1.4000	〉0.05
Sleep Deprivation x Time-On-Task x Driving Load x Subjects	18	4860.8700	270		
Time-On-Task x ATIS Complexity x Driving Load	4	1902.9300	476	0.9600	〉0.05
Time-On-Task x ATIS Complexity x Driving Load x Subjects	36	17772.3700	494		
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load	6	2478.8200	413	1.0900	〉0.05
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load x Subjects	54	20543.4000	380		

Table 3. Multivariate analysis of variance for standard deviation ratings of driving speed.

Source	df	SS	MS	F	p
Sleep Deprivation	1	0.4519	0	4.7600	〉0.05
Sleep Deprivation x Subjects	9	0.8552	0		
Time-On-Task	**2**	**0.6830**	**0**	**3.9300**	**0.05**
Time-On-Task x Subjects	18	1.5655	0		
ATIS Complexity	2	0.0153	0	0.3800	〉0.05
ATIS Complexity x Subjects	18	0.3618	0		
Driving Load	1	0.0880	0	3.3400	〉0.05
Driving Load x Subjects	9	0.2368	0		
Sleep Deprivation x Time-On-Task	2	0.1177	0	3.2500	〉0.05
Sleep Deprivation x Time-On-Task x Subjects	18	0.3261	0		
Sleep Deprivation x ATIS Complexity	2	0.0530	0	2.1600	〉0.05
Sleep Deprivation x ATIS Complexity x Subjects	18	0.2204	0		
Sleep Deprivation x Driving Load	1	0.0427	0	0.6400	〉0.05
Sleep Deprivation x Driving Load x Subjects	9	0.6051	0		
Time-On-Task x ATIS Complexity	4	0.0855	0	0.3500	〉0.05
Time-On-Task x ATIS Complexity x Subjects	36	2.1784	0		
Time-On-Task x Driving Load	2	0.0097	0	0.3600	〉0.05
Time-On-Task x Driving Load x Subjects	18	0.2458	0		
ATIS Complexity x Driving Load	2	0.0014	0	0.0400	〉0.05
ATIS Complexity x Driving Load x Subjects	18	0.2801	0		
Sleep Deprivation x Time-On-Task x ATIS Complexity	4	0.0244	0	0.3700	〉0.05
Sleep Deprivation x Time-On-Task x ATIS Complexity x Subjects	36	0.6005	0		
Sleep Deprivation x Time-On-Task x Driving Load	2	0.0216	0	1.3400	〉0.05
Sleep Deprivation x Time-On-Task x Driving Load x Subjects	18	0.1447	0		
Time-On-Task x ATIS Complexity x Driving Load	4	0.0975	0	2.1600	〉0.05
Time-On-Task x ATIS Complexity x Driving Load x Subjects	36	0.4066	0		
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load	6	0.0523	0	0.2800	〉0.05
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load x Subjects	54	1.6915	0		

Table 4. Multivariate analysis of variance for standard deviation ratings of longitudinal acceleration.

Source	df	SS	MS	F	p
Sleep Deprivation	1	0.0029	0.0029	1.25	0.293
Sleep Deprivation x Subjects	9	0.0207	0.0023		
Time-On-Task	2	0.0180	0.0090	3.27	0.061
Time-On-Task x Subjects	18	0.0496	0.0028		
ATIS Complexity	2	0.0006	0.0003	1.01	0.383
ATIS Complexity x Subjects	18	0.0049	0.0003		
Driving Load	**1**	**0.0099**	**0.0099**	**10.97**	**0.009**
Driving Load x Subjects	9	0.0081	0.0009		
Sleep Deprivation x Time-On-Task	2	0.0023	0.0011	2.60	0.102
Sleep Deprivation x Time-On-Task x Subjects	18	0.0078	0.0004		
Sleep Deprivation x ATIS Complexity	2	0.0006	0.0003	2.47	0.113
Sleep Deprivation x ATIS Complexity x Subjects	18	0.0022	0.0001		
Sleep Deprivation x Driving Load	1	0.0008	0.0008	0.55	0.478
Sleep Deprivation x Driving Load x Subjects	9	0.0123	0.0014		
Time-On-Task x ATIS Complexity	4	0.0040	0.0010	0.72	0.585
Time-On-Task x ATIS Complexity x Subjects	36	0.0497	0.0014		
Time-On-Task x Driving Load	2	0.0009	0.0005	0.75	0.485
Time-On-Task x Driving Load x Subjects	18	0.0112	0.0006		
ATIS Complexity x Driving Load	2	0.0000	0.0000	0.01	0.990
ATIS Complexity x Driving Load x Subjects	18	0.0063	0.0003		
Sleep Deprivation x Time-On-Task x ATIS Complexity	4	0.0007	0.0002	0.73	0.575
Sleep Deprivation x Time-On-Task x ATIS Complexity x Subjects	36	0.0091	0.0003		
Sleep Deprivation x Time-On-Task x Driving Load	2	0.0006	0.0003	0.93	0.411
Sleep Deprivation x Time-On-Task x Driving Load x Subjects	18	0.0062	0.0003		
Time-On-Task x ATIS Complexity x Driving Load	**4**	**0.0049**	**0.0012**	**3.38**	**0.019**
Time-On-Task x ATIS Complexity x Driving Load x Subjects	36	0.0129	0.0004		
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load	6	0.0016	0.0003	0.42	0.865
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load x Subjects	54	0.0346	0.0006		

Table 5. Multivariate analysis of variance for standard deviation ratings of lane position.

Source	df	SS	MS	F	p
Sleep Deprivation	1	2.2529	2.2529	4.33	0.067
Sleep Deprivation x Subjects	9	4.6830	0.5203		
Time-On-Task	**2**	**9.3945**	**4.6973**	**6.96**	**0.006**
Time-On-Task x Subjects	18	12.1508	0.6750		
ATIS Complexity	2	0.5613	0.2807	3.17	0.066
ATIS Complexity x Subjects	18	1.5953	0.0886		
Driving Load	1	0.0005	0.0005	0.00	0.952
Driving Load x Subjects	9	1.2983	0.1443		
Sleep Deprivation x Time-On-Task	2	0.7539	0.3769	2.36	0.123
Sleep Deprivation x Time-On-Task x Subjects	18	2.8704	0.1595		
Sleep Deprivation x ATIS Complexity	**2**	**0.4351**	**0.2176**	**5.72**	**0.012**
Sleep Deprivation x ATIS Complexity x Subjects	18	0.6844	0.0380		
Sleep Deprivation x Driving Load	1	0.0001	0.0001	0.00	0.987
Sleep Deprivation x Driving Load x Subjects	9	3.2142	0.3571		
Time-On-Task x ATIS Complexity	4	0.1578	0.0395	1.76	0.159
Time-On-Task x ATIS Complexity x Subjects	36	0.8072	0.0224		
Time-On-Task x Driving Load	2	0.1636	0.0818	1.26	0.307
Time-On-Task x Driving Load x Subjects	18	1.1679	0.0649		
ATIS Complexity x Driving Load	2	0.1149	0.0575	2.54	0.106
ATIS Complexity x Driving Load x Subjects	18	0.4064	0.0226		
Sleep Deprivation x Time-On-Task x ATIS Complexity	**4**	**0.3721**	**0.0930**	**3.95**	**0.009**
Sleep Deprivation x Time-On-Task x ATIS Complexity x Subjects	36	0.8485	0.0236		
Sleep Deprivation x Time-On-Task x Driving Load	2	0.0323	0.0161	0.35	0.709
Sleep Deprivation x Time-On-Task x Driving Load x Subjects	18	0.8273	0.0460		
Time-On-Task x ATIS Complexity x Driving Load	4	0.1312	0.0328	0.70	0.599
Time-On-Task x ATIS Complexity x Driving Load x Subjects	36	1.6944	0.0471		
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load	6	0.2626	0.0438	1.78	0.120
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load x Subjects	54	1.3246	0.0245		

Table 6. Two-way analysis of variance for lane position deviations at the sleep-deprived condition.

Source	df	SS	MS	F	p
Time-On-Task	**2**	**7.5890**	**4**	**9.1800**	**0**
Time-On-Task x Subjects	18	1.8430	0		
ATIS Complexity	2	0.2290	0	1.1200	0
ATIS Complexity x Subjects	18	7.4370	0		
ATIS Complexity x Time-On-Task	**4**	**0.3490**	**0**	**3.6200**	**0**
ATIS Complexity x Time-On-Task x Subjects	36	0.8680	0		

Table 7. Two-way analysis of variance for lane position deviations at the non-sleep-deprived condition.

Source	df	SS	MS	F	p
Time-On-Task	2	2.5590	1	3.0400	0
Time-On-Task x Subjects	18	0.4370	0		
ATIS Complexity	**2**	**0.7680**	**0**	**15.8200**	**<0.001**
ATIS Complexity x Subjects	18	7.5850	0		
ATIS Complexity x Time-On-Task	4	0.1810	0	2.0700	0
ATIS Complexity x Time-On-Task x Subjects	36	0.7870	0		

Table 8. Multivariate analysis of variance for response latency in ATIS task.

Source	df	SS	MS	F	p
Sleep Deprivation	1	4.7700	4.77	3.61	0.090
Sleep Deprivation x Subjects	9	11.8900	1.32		
Time-On-Task	2	1.2700	0.64	2.59	0.103
Time-On-Task x Subjects	18	4.4100	0.25		
ATIS Complexity	1	0.4900	0.49	1.89	0.203
ATIS Complexity x Subjects	9	2.3400	0.26		
Driving Load	1	0.0200	0.02	0.07	0.802
Driving Load x Subjects	9	3.2100	0.36		
Information Modality	**1**	**68.6400**	**68.64**	**34.66**	**<0.001**
Information Modality x Subjects	9	17.8200	1.98		
Sleep Deprivation x Time-On-Task	2	1.2100	0.60	1.30	0.296
Sleep Deprivation x Time-On-Task x Subjects	18	8.3400	0.46		
Sleep Deprivation x ATIS Complexity	1	0.0300	0.03	0.22	0.649
Sleep Deprivation x ATIS Complexity x Subjects	9	1.3400	0.15		
Sleep Deprivation x Driving Load	1	0.2000	0.20	0.80	0.394
Sleep Deprivation x Driving Load x Subjects	9	2.2900	0.25		
Sleep Deprivation x Information Modality	1	0.1400	0.14	0.46	0.515
Sleep Deprivation x Information Modality x Subjects	9	2.6700	0.30		
Time-On-Task x ATIS Complexity	2	0.3700	0.18	1.21	0.321
Time-On-Task x ATIS Complexity x Subjects	18	2.7200	0.15		
Time-On-Task x Driving Load	2	0.0100	0.00	0.01	0.992
Time-On-Task x Driving Load x Subjects	18	6.0900	0.34		
Time-On-Task x Information Modality	**2**	**1.5300**	**0.77**	**5.33**	**0.015**
Time-On-Task x Information Modality x Subjects	18	2.5900	0.14	1.12	
ATIS Complexity x Driving Load	**1**	**0.9600**	**0.96**	**7.03**	**0.026**
ATIS Complexity x Driving Load x Subjects	9	1.2300	0.14		
ATIS Complexity x Information Modality	**1**	**0.8500**	**0.85**	**16.39**	**0.003**
ATIS Complexity x Information Modality x Subjects	9	0.4700	0.05		
Driving Load x Information Modality	1	0.0000	0.00	0.01	0.945
Driving Load x Information Modality x Subjects	9	1.0200	0.11		
Sleep Deprivation x Time-On-Task x ATIS Complexity	3	0.1000	0.03	0.21	0.888
Sleep Deprivation x Time-On-Task x ATIS Complexity x Subjects	27	4.4000	0.16		
Sleep Deprivation x Time-On-Task x Driving Load	3	0.3700	0.12	0.39	0.760
Sleep Deprivation x Time-On-Task x Driving Load x Subjects	27	8.5600	0.32		
Sleep Deprivation x Time-On-Task x Information Modality	3	0.6900	0.23	1.23	0.319
Sleep Deprivation x Time-On-Task x Information Modality x Subjects	27	5.0600	0.19		

Table 8. Multivariate analysis of variance for response latency in ATIS task (continued).

Source	df	SS	MS	F	p
Time-On-Task x ATIS Complexity x Driving Load	2	0.1900	0	0.6900	〉0.05
Time-On-Task x ATIS Complexity x Driving Load x Subjects	18	2.4700	0		
Time-On-Task x ATIS Complexity x Information Modality	2	0.0300	0	0.2700	〉0.05
Time-On-Task x ATIS Complexity x Information Modality x Subjects	18	1.0700	0		
ATIS Complexity x Driving Load x Information Modality	2	0.5100	0	1.8500	〉0.05
ATIS Complexity x Driving Load x Information Modality x Subjects	18	2.5000	0		
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load	6	0.6500	0	0.5000	〉0.05
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load x Subjects	54	11.5800	0		
Sleep Deprivation x Time-On-Task x ATIS Complexity x Information Modality	6	0.9000	0	0.9200	〉0.05
Sleep Deprivation x Time-On-Task x ATIS Complexity x Information Modality x Subjects	54	8.7400	0		
Time-On-Task x ATIS Complexity x Driving Load x Information Modality	6	1.4900	0	2.0700	〉0.05
Time-On-Task x ATIS Complexity x Driving Load x Information Modality x Subjects	54	6.4600	0		
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load x Information Modality	6	0.4100	0	0.5700	〉0.05
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load x Information Modality x Subjects	54	6.5200	0		

Table 9. Multivariate analysis of variance for mean eye ramp closure.

Source	df	SS	MS	F	p
Sleep Deprivation	**1**	**6537.5500**	**6537.55**	**13.15**	**0.006**
Sleep Deprivation x Subjects	9	4475.3300	497.26		
Time-On-Task	**2**	**3304.0300**	**1652.02**	**5.37**	**0.015**
Time-On-Task x Subjects	18	5535.2200	307.51		
ATIS Complexity	2	10.3000	5.15	0.15	0.859
ATIS Complexity x Subjects	18	603.6900	33.54		
Driving Load	1	7.9500	7.95	0.27	0.616
Driving Load x Subjects	9	265.3000	29.48		
Sleep Deprivation x Time-On-Task	2	89.0000	44.50	0.54	0.590
Sleep Deprivation x Time-On-Task x Subjects	18	1471.8200	81.77		
Sleep Deprivation x ATIS Complexity	2	27.5800	13.79	0.49	0.622
Sleep Deprivation x ATIS Complexity x Subjects	18	509.0600	28.28		
Sleep Deprivation x Driving Load	1	12.6400	12.64	0.13	0.726
Sleep Deprivation x Driving Load x Subjects	9	867.7600	96.42		
Time-On-Task x ATIS Complexity	4	100.8400	25.21	1.47	0.231
Time-On-Task x ATIS Complexity x Subjects	36	616.3200	17.12		
Time-On-Task x Driving Load	2	69.3800	34.69	1.64	0.222
Time-On-Task x Driving Load x Subjects	18	380.6600	21.15		
ATIS Complexity x Driving Load	2	44.3400	22.17	0.93	0.412
ATIS Complexity x Driving Load x Subjects	18	428.0000	23.78		
Sleep Deprivation x Time-On-Task x ATIS Complexity	4	86.1700	21.54	1.83	0.145
Sleep Deprivation x Time-On-Task x ATIS Complexity x Subjects	36	424.3200	11.79		
Sleep Deprivation x Time-On-Task x Driving Load	2	64.2100	32.10	2.24	0.135
Sleep Deprivation x Time-On-Task x Driving Load x Subjects	18	257.9100	14.33		
Time-On-Task x ATIS Complexity x Driving Load	4	35.9000	8.98	0.51	0.726
Time-On-Task x ATIS Complexity x Driving Load x Subjects	36	628.4300	17.46		
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load	**6**	**353.6300**	**58.94**	**2.69**	**0.023**
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load x Subjects	54	1181.9100	21.89		

Table 10. Multivariate analysis of variance for mean eye ramp position for sleep deprivation, non-sleep-deprived condition.

Source	df	SS	MS	F	p
Time-On-Task	**2**	**2212.91**	**1106.46**	**6.71**	**0.007**
Driving Load x Subjects	18	2969.29	164.96		
ATIS Complexity	2	3.15	1.57	0.05	0.954
Time-On-Task x Subjects	18	592.80	32.93		
Driving Load	1	20.31	20.31	0.45	0.521
ATIS Complexity x Subjects	9	409.42	45.49		
Driving Load x Time-On-Task	**4**	**155.30**	**38.82**	**3.37**	**0.019**
Driving Load x Time-On-Task x Subjects	36	415.06	11.53		
Driving Load x ATIS Complexity	2	57.31	28.66	2.40	0.119
Driving Load x ATIS Complexity x Subjects	18	215.17	11.95		
Time-On-Task x ATIS Complexity	2	46.63	23.32	1.31	0.294
Time-On-Task x ATIS Complexity x Subjects	18	319.67	17.76		
Driving Load x Time-On-Task x ATIS Complexity	4	104.04	26.01	1.45	0.238
Driving Load x Time-On-Task x ATIS Complexity x Subjects	36	646.27	17.95		

Table 11. Multivariate analysis of variance for mean eye ramp position for sleep deprivation, no sleep condition.

Source	df	SS	MS	F	p
Time-On-Task	2	1180.12	590.06	2.63	0.100
Driving Load x Subjects	18	4037.75	224.32		
ATIS Complexity	2	34.74	17.37	0.60	0.559
Time-On-Task x Subjects	18	519.95	28.89		
Driving Load	1	0.27	0.27	0.00	0.955
ATIS Complexity x Subjects	9	723.64	80.40		
Driving Load x Time-On-Task	4	31.72	7.93	0.46	0.767
Driving Load x Time-On-Task x S	36	625.57	17.38		
Driving Load x ATIS Complexity	2	76.27	38.14	1.62	0.225
Driving Load x ATIS Complexity x S	18	423.40	23.52		
Time-On-Task x ATIS Complexity	2	81.61	40.80	1.38	0.277
Time-On-Task x ATIS Complexity x S	18	532.69	29.59		
Driving Load x Time-On-Task x C	4	201.60	50.40	2.45	0.063
Driving Load x Time-On-Task x ATIS Complexity x Subjects	36	739.71	20.55		

Table 12. Multivariate analysis of variance for mean percentage of time when the eye ramp was 80 percent to 100 percent closed.

Source	df	SS	MS	F	p
Sleep Deprivation	**1**	**232.6700**	**232.67**	**15.21**	**0.004**
Sleep Deprivation x Subjects	9	137.6900	15.30		
Time-On-Task	2	74.9900	37.49	2.47	0.112
Time-On-Task x Subjects	18	272.7400	15.15		
ATIS Complexity	2	1.7700	0.88	0.17	0.843
ATIS Complexity x Subjects	18	92.4600	5.14		
Driving Load	1	0.0400	0.04	0.03	0.876
Driving Load x Subjects	9	13.8900	1.54		
Sleep Deprivation x Time-On-Task	2	0.9700	0.49	0.07	0.933
Sleep Deprivation x Time-On-Task x Subjects	18	126.0200	7.00		
Sleep Deprivation x ATIS Complexity	2	6.9500	3.47	2.90	0.081
Sleep Deprivation x ATIS Complexity x Subjects	18	21.5800	1.20		
Sleep Deprivation x Driving Load	1	0.0800	0.08	0.02	0.886
Sleep Deprivation x Driving Load x Subjects	9	32.6700	3.63	0.0000	0
Time-On-Task x ATIS Complexity	4	6.5500	1.64	1.40	0.252
Time-On-Task x ATIS Complexity x Subjects	36	41.9300	1.16		
Time-On-Task x Driving Load	2	8.5100	4.26	2.20	0.140
Time-On-Task x Driving Load x Subjects	18	34.9000	1.94		
ATIS Complexity x Driving Load	2	6.8400	3.42	2.99	0.076
ATIS Complexity x Driving Load x Subjects	18	20.6200	1.15		
Sleep Deprivation x Time-On-Task x ATIS Complexity	4	3.3300	0.83	0.80	0.532
Sleep Deprivation x Time-On-Task x ATIS Complexity x Subjects	36	37.2800	1.04		
Sleep Deprivation x Time-On-Task x Driving Load	2	3.5500	1.77	1.18	0.330
Sleep Deprivation x Time-On-Task x Driving Load x Subjects	18	27.0300	1.50		
Time-On-Task x ATIS Complexity x Driving Load	4	3.9800	0.99	0.75	0.567
Time-On-Task x ATIS Complexity x Driving Load x Subjects	36	47.9700	1.33		
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load	6	3.1700	0.53	0.48	0.820
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load x Subjects	54	59.4100	1.10		

Table 13.
Multivariate analysis of variance for seven-point subjective fatigue rating during experiment.

Source	df	SS	MS	F	p
Sleep Deprivation	**1**	**324.9000**	**324.90**	**22.25**	**<0.001**
Sleep Deprivation x Subjects	9	131.4300	14.60		
Time-On-Task	**2**	**151.5500**	**75.78**	**29.86**	**<0.001**
Time-On-Task x Subjects	18	45.6700	2.54		
ATIS Complexity	2	0.4200	0.21	0.63	0.545
ATIS Complexity x Subjects	18	5.9700	0.33		
Driving Load	**1**	**2.1800**	**2.18**	**5.62**	**0.042**
Driving Load x Subjects	9	3.4900	0.39		
Sleep Deprivation x Time-On-Task	2	1.2500	0.63	0.21	0.809
Sleep Deprivation x Time-On-Task x Subjects	18	52.4200	2.91		
Sleep Deprivation x ATIS Complexity	2	1.1200	0.56	2.70	0.094
Sleep Deprivation x ATIS Complexity x Subjects	18	3.7200	0.21		
Sleep Deprivation x Driving Load	1	0.7100	0.71	0.24	0.634
Sleep Deprivation x Driving Load x Subjects	9	26.4000	2.93		
Time-On-Task x ATIS Complexity	4	0.3800	0.10	0.34	0.847
Time-On-Task x ATIS Complexity x Subjects	36	10.0600	0.28		
Time-On-Task x Driving Load	2	0.4400	0.22	0.76	0.484
Time-On-Task x Driving Load x Subjects	18	5.2300	0.29		
ATIS Complexity x Driving Load	2	0.0400	0.02	0.06	0.942
ATIS Complexity x Driving Load x Subjects	18	5.7900	0.32		
Sleep Deprivation x Time-On-Task x ATIS Complexity	4	0.2800	0.07	0.58	0.678
Sleep Deprivation x Time-On-Task x ATIS Complexity x Subjects	36	4.3800	0.12		
Sleep Deprivation x Time-On-Task x Driving Load	2	0.3400	0.17	0.21	0.809
Sleep Deprivation x Time-On-Task x Driving Load x Subjects	18	14.2200	0.79		
Time-On-Task x ATIS Complexity x Driving Load	4	0.7900	0.20	0.84	0.511
Time-On-Task x ATIS Complexity x Driving Load x Subjects	36	8.5400	0.24		
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load	6	1.9000	0.32	0.95	0.465
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load x Subjects	54	17.9300	0.33		

Table 14. Multivariate analysis of variance for subjective time stress rating.

Source	df	SS	MS	F	p
Sleep Deprivation	**1**	**19.1400**	**19.14**	**6.51**	**0.031**
Sleep Deprivation x Subjects	9	26.4500	2.94		
Time-On-Task	**2**	**7.4400**	**3.72**	**9.41**	**0.002**
Time-On-Task x Subjects	18	7.1200	0.40		
ATIS Complexity	**2**	**7.6200**	**3.81**	**8.65**	**0.002**
ATIS Complexity x Subjects	18	7.9300	0.44		
Driving Load	**1**	**0.8000**	**0.80**	**10.79**	**0.010**
Driving Load x Subjects	9	0.6700	0.07		
Sleep Deprivation x Time-On-Task	2	1.8700	0.94	2.75	0.091
Sleep Deprivation x Time-On-Task x Subjects	18	6.1300	0.34		
Sleep Deprivation x ATIS Complexity	2	0.0200	0.01	0.31	0.737
Sleep Deprivation x ATIS Complexity x Subjects	18	0.6400	0.04		
Sleep Deprivation x Driving Load	4	0.1800	0.04	0.38	0.825
Sleep Deprivation x Driving Load x Subjects	9	5.0300	0.56		
Time-On-Task x ATIS Complexity	1	0.3400	0.34	0.60	0.458
Time-On-Task x ATIS Complexity x Subjects	36	4.2700	0.12		
Time-On-Task x Driving Load	2	0.0100	0.00	0.03	0.972
Time-On-Task x Driving Load x Subjects	18	1.7700	0.10		
ATIS Complexity x Driving Load	2	0.2900	0.14	1.43	0.266
ATIS Complexity x Driving Load x Subjects	18	1.8200	0.10		
Sleep Deprivation x Time-On-Task x ATIS Complexity	4	0.3400	0.09	0.85	0.504
Sleep Deprivation x Time-On-Task x ATIS Complexity x Subjects	36	3.6600	0.10		
Sleep Deprivation x Time-On-Task x Driving Load	2	0.1100	0.05	0.39	0.684
Sleep Deprivation x Time-On-Task x Driving Load x Subjects	18	2.4500	0.14		
Time-On-Task x ATIS Complexity x Driving Load	**4**	**1.2800**	**0.32**	**3.18**	**0.024**
Time-On-Task x ATIS Complexity x Driving Load x Subjects	36	3.6100	0.10		
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load	6	0.5300	0.09	0.62	0.717
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load x Subjects	54	7.8000	0.14		

Table 15. Two-way analysis of variance for subjective time stress rating at the first time-on-task condition.

Source	df	SS	MS	F	p
ATIS Complexity	**2**	**1.6080**	**0.804**	**5.85**	**0.011**
ATIS Complexity x Subjects	18	2.4750	0.138		
Driving Load	1	0.1500	0.150	3.86	0.081
Driving Load x Subjects	9	0.3500	0.039		
ATIS Complexity x Time-On-Task	2	0.4750	0.238	3.35	0.058
ATIS Complexity x Time-On-Task x Subjects	18	1.2750	0.071		

Table 16. Two-way analysis of variance for subjective time stress rating at the second time-on-task condition.

Source	df	SS	MS	F	p
ATIS Complexity	**2**	**1.2580**	**0.629**	**5.93**	**0.011**
ATIS Complexity x Subjects	18	1.9080	0.106		
Driving Load	1	0.1040	0.104	1.80	0.213
Driving Load x Subjects	9	0.5210	0.058		
ATIS Complexity x Time-On-Task	2	0.2080	0.104	2.37	0.122
ATIS Complexity x Time-On-Task x Subjects	18	0.7920	0.044		

Table 17. Two-way analysis of variance for subjective time stress rating at the third time-on-task condition.

Source	df	SS	MS	F	p
ATIS Complexity	**2**	**1.0330**	**0.517**	**5.42**	**0.014**
ATIS Complexity x Subjects	18	1.7170	0.095		
Driving Load	1	0.1500	0.15	3.86	0.081
Driving Load x Subjects	9	0.3500	0.04		
ATIS Complexity x Time-On-Task	2	0.1000	0.05	1.38	0.276
ATIS Complexity x Time-On-Task x Subjects	18	0.6500	0.04		

Table 18. Multivariate analysis of variance for subjective visual effort rating.

Source	df	SS	MS	F	p
Sleep Deprivation	**1**	**13.2300**	**13.23**	**5.50**	**0.044**
Sleep Deprivation x Subjects	9	21.6400	2.40		
Time-On-Task	**2**	**8.6200**	**4.31**	**7.24**	**0.005**
Time-On-Task x Subjects	18	10.7100	0.60		
ATIS Complexity	**2**	**10.6900**	**5.34**	**13.79**	**0**
ATIS Complexity x Subjects	18	6.9800	0.39		
Driving Load	**1**	**3.8000**	**3.80**	**9.77**	**0.012**
Driving Load x Subjects	9	3.5000	0.39		
Sleep Deprivation x Time-On-Task	2	1.2700	0.63	1.04	0.374
Sleep Deprivation x Time-On-Task x Subjects	18	10.9600	0.61		
Sleep Deprivation x ATIS Complexity	2	0.8000	0.40	2.33	0.126
Sleep Deprivation x ATIS Complexity x Subjects	18	3.0900	0.17		
Sleep Deprivation x Driving Load	1	0.2300	0.23	0.42	0.535
Sleep Deprivation x Driving Load x Subjects	9	4.8600	0.54		
Time-On-Task x ATIS Complexity	4	0.8800	0.22	1.36	0.266
Time-On-Task x ATIS Complexity x Subjects	36	5.7900	0.16		
Time-On-Task x Driving Load	2	0.6200	0.31	1.98	0.166
Time-On-Task x Driving Load x Subjects	18	2.8200	0.16		
ATIS Complexity x Driving Load	2	0.0900	0.04	0.22	0.807
ATIS Complexity x Driving Load x Subjects	18	3.6900	0.20		
Sleep Deprivation x Time-On-Task x ATIS Complexity	4	0.8300	0.21	1.52	0.218
Sleep Deprivation x Time-On-Task x ATIS Complexity x Subjects	36	4.9400	0.14		
Sleep Deprivation x Time-On-Task x Driving Load	2	0.2000	0.10	0.52	0.604
Sleep Deprivation x Time-On-Task x Driving Load x Subjects	18	3.4700	0.19		
Time-On-Task x ATIS Complexity x Driving Load	4	0.3100	0.08	0.57	0.686
Time-On-Task x ATIS Complexity x Driving Load x Subjects	36	4.9100	0.14		
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load	6	1.0000	0.17	1.12	0.360
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load x Subjects	54	8.0000	0.15		

Table 19. Multivariate analysis of variance for subjective psychological stress.

Source	df	SS	MS	F	p
Sleep Deprivation	**1**	**38.6800**	**38.68**	**10.94**	**0.009**
Sleep Deprivation x Subjects	9	31.8200	3.54		
Time-On-Task	**2**	**11.3600**	**5.68**	**6.95**	**0.006**
Time-On-Task x Subjects	18	14.7000	0.82		
ATIS Complexity	**2**	**2.1100**	**1.05**	**5.24**	**0.016**
ATIS Complexity x Subjects	18	3.6200	0.20		
Driving Load	**1**	**0.9000**	**0.90**	**8.68**	**0.016**
Driving Load x Subjects	9	0.9300	0.10		
Sleep Deprivation x Time-On-Task	2	0.4200	0.21	0.36	0.699
Sleep Deprivation x Time-On-Task x Subjects	18	10.4100	0.58		
Sleep Deprivation x ATIS Complexity	2	0.1100	0.05	0.35	0.711
Sleep Deprivation x ATIS Complexity x Subjects	18	2.7300	0.15		
Sleep Deprivation x Driving Load	1	0.0100	0.01	0.03	0.858
Sleep Deprivation x Driving Load x Subjects	9	2.9300	0.33		
Time-On-Task x ATIS Complexity	4	0.9100	0.23	1.32	0.280
Time-On-Task x ATIS Complexity x Subjects	36	6.2000	0.17		
Time-On-Task x Driving Load	2	0.2000	0.10	0.92	0.418
Time-On-Task x Driving Load x Subjects	18	1.9700	0.11		
ATIS Complexity x Driving Load	2	0.2200	0.11	0.66	0.528
ATIS Complexity x Driving Load x Subjects	18	2.9500	0.16		
Sleep Deprivation x Time-On-Task x ATIS Complexity	4	0.3400	0.09	0.62	0.650
Sleep Deprivation x Time-On-Task x ATIS Complexity x Subjects	36	4.9900	0.14		
Sleep Deprivation x Time-On-Task x Driving Load	2	0.2900	0.14	0.40	0.674
Sleep Deprivation x Time-On-Task x Driving Load x Subjects	18	6.4300	0.36		
Time-On-Task x ATIS Complexity x Driving Load	**4**	**1.2300**	**0.31**	**2.71**	**0.045**
Time-On-Task x ATIS Complexity x Driving Load x Subjects	36	4.1000	0.11		
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load	6	0.5500	0.09	0.68	0.667
Sleep Deprivation x Time-On-Task x ATIS Complexity x Driving Load x Subjects	54	7.2800	0.13		

Table 20. Two-way analysis of variance for subjective psychological stress rating at the first time-on-task condition.

Source	df	SS	MS	F	p
ATIS Complexity	**2**	**0.9330**	**0.467**	**6.38**	**0.008**
ATIS Complexity x Subjects	18	1.3170	0.073		
Driving Load	1	0.0670	0.067	0.88	0.373
Driving Load x Subjects	9	0.6830	0.076		
ATIS Complexity x Time-On-Task	2	0.0330	0.017	0.42	0.664
ATIS Complexity x Time-On-Task x Subjects	18	0.7170	0.040		

Table 21. Two-way analysis of variance for subjective psychological stress rating at the second time-on-task condition.

Source	df	SS	MS	F	p
ATIS Complexity	2	0.4750	0.238	1.81	0.192
ATIS Complexity x Subjects	18	2.3580	0.131		
Driving Load	1	0.0670	0.067	1.38	0.270
Driving Load x Subjects	9	0.4330	0.048		
ATIS Complexity x Time-On-Task	2	0.2580	0.129	1.87	0.183
ATIS Complexity x Time-On-Task x Subjects	18	1.2420	0.069		

Table 22. Two-way analysis of variance for subjective psychological stress rating at the third time-on-task condition.

Source	df	SS	MS	F	p
ATIS Complexity	2	0.1000	0.050	0.73	0.496
ATIS Complexity x Subjects	18	1.2330	0.069		
Driving Load	**1**	**0.4170**	**0.417**	**11.25**	**0.009**
Driving Load x Subjects	9	0.3330	0.037		
ATIS Complexity x Time-On-Task	2	0.4330	0.217	2.49	0.111
ATIS Complexity x Time-On-Task x Subjects	18	1.5670	0.087		

APPENDIX B

Uni-dimensional scale employed within each time-on-task condition

Q. PLEASE REPORT THE NUMBER OF THE STATEMENT THAT DESCRIBES HOW YOU FEEL RIGHT NOW.....( )

1. Fully alert, wide awake, very peppy

2. Very lively, responsive, not at peak

3. Okay, somewhat fresh

4. A little tired, less than fresh

5. Moderately let down

6. Extremely tired

7. Completely exhausted, unable to function

APPENDIX C

Multi-dimensional scale employed before and after the experiment

Condition (fatigue/non-fatigue)
Subject #:_____

Q. PLEASE ANSWER YES OR NO, BASED ON THE SYMPTOMS YOU EXPERIENCE RIGHT NOW.

Yes No

1. Feel heavy in the head_____
2. Get tired over the whole body_____
3. Get tired in the legs_____
4. Give a yawn_____
5. Feel the brain hot or muddled_____
6. Become drowsy_____
7. Feel strain in the eyes_____
8. Become rigid or clumsy in motion_____

9. Find difficulty in thinking_____
10. Become nervous_____
11. Unable to concentrate attention_____
12. Unable to have interest in thinking_____
13. Become apt to forget things_____
14. Lack of self-confidence_____
15. Anxious about things_____
16. Lack patience_____

17. Have a headache_____
18. Feel stiff in the shoulders_____
19. Feel a pain in the waist_____
20. Feel constrained in breathing_____
21. Feel thirsty_____
22. Have dizziness_____
23. Have a spasm in the eye lids_____
24. Have a tremor in the limbs_____
25. Feel ill_____

Subjective Fatigue Scores are calculated as:

$$\text{Frequency of complaint of fatigue} = \frac{\text{Number of "Yes" answers}}{\text{Number of items}} \times 100$$

Dimensions in this subjective fatigue scale:

1. Drowsiness and dullness: item #1 - #8
2. Difficulty in concentration: item #9-#16
3. Projection of physical impairment: item #17-#25

APPENDIX D

INFORMATION SUMMARY

Project Title: **CVO DRIVER FATIGUE AND COMPLEX IN-VEHICLE SYSTEMS**
Investigators: Tom Dingus and Jaesik Lee

Thank you for coming in today. The purpose of the study is to determine how fatigue impacts a CVO driver's ability to interact with complex in-vehicle systems. We will be gathering information and input to determine how you drive the driving simulator when you are fatigued or non-fatigued.

If you agree to participate, you will be asked to drive the driving simulator and to fill out several questionnaires. Your participation should take approximately 12 hours. For your participation you will receive $15.00 an hour.

You should know that a small number of people experience something similar to motion sickness when operating simulators. The effects are typically slight and usually consist of an odd feeling or warmth which lasts only 10-15 minutes. If you feel uncomfortable, you may ask to quit at any time. Most people enjoy driving the simulator and do not experience any discomfort.

All information gathered in this study will be kept confidential. Your participation is voluntary. You may discontinue participation at any time without penalty or loss of benefits to which you are entitled. You should understand that you have the right to ask questions at any time and that you can contact Tom Dingus at 335-5696 for information about the study and your rights.

You should understand that in the event of physical injury resulting directly from the research procedures, no compensation will be available in the absence of negligence by a state employee. However, medical treatment is available at the University Hospitals and Clinics, but you will be responsible for making arrangements for payment of the expenses of such treatment. Further information may be obtained from Dorothy M. Maher, Division of Sponsored Programs, Office of the Vice-President for Research, 319-335-2123.

A record of your responses and driving performance will be maintained for future use. This record will be kept confidential and will be stored without reference to your personal identity.

Again, thank you.

I have discussed the above points, including the information required by the Iowa Fair Information Practices Act, with the subject or the legally authorized representative, using a translator when necessary. It is my opinion that the subject understands the risks, benefits, and obligations involved in participation in this project.

_____	_____	_____	_____
Investigator	Date	Witness	Date

APPENDIX E

INFORMED CONSENT FORM

Project Title: CVO driver fatigue and complex in-vehicle system

Investigators: Tom Dingus and Jaesik Lee

I certify that I have been informed about the study in which I am about to participate. I have been told the procedures to be followed and how much time and compensation is involved. I have also been told that all records which may identify me will be kept confidential. I understand the possible risks and the possible benefits to me and to others from the research.

I have been given adequate time to read the attached summary. I understand that I have the right to ask questions at any time and that I can contact Tom Dingus at 335-5696 for information about the research and my rights.

I understand that my participation is voluntary and that I may refuse to participate or withdraw my consent and stop taking part at any time without penalty or loss of benefits to which I may be entitled. I hereby consent to take part in this project.

_____ _____

Signature of the Participant Date

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