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The Effect of Sleep Deprivation on Driving Performance

Final Report

Prepared by:

John Bloomfield
Kathleen A. Harder
Benjamin J. Chihak

Center for Human Factors Systems Research and Design
University of Minnesota

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16. Abstract (Limit: 250 words)

Each of twenty commercial motor vehicle (CMV) drivers participated in a single twenty-hour experimental session, during which they were continuously kept awake, but were allowed to ingest caffeine and use tobacco as they would in real-world conditions. Each participant drove in a fixed-base advanced driving simulator for approximately one hour on four occasions (at 9:00 am, 3:00 pm, 9:00 pm, and 3:00 am). The 59.5-mile (95.8-km) test route was designed with overpasses and intersections and changes in speed limits—to make the driving experience more like real-word driving. After the fourth drive, the participants were driven to the University of Minnesota's General Clinical Research Center, where they slept for eight hours.

The main result was that the steering performance of CMV drivers was impaired when they stayed awake for an extended period: There was a considerable increase in steering instability between the morning drive, at 9:00 am, and the nighttime drive, at 3:00 pm—an increase likely to have been produced by sleep deprivation.
[Other results were: (1) stopping behavior improved throughout the session—suggesting practice effects; (2) after the fourth drive, there was less reduction in the participants' pupil size—but, since there was no difference in pupil size before the fourth drive, there was no evidence to suggest that pupil size reductions could be used to predict sleep deprivation; (3) data from other visual performance tests showed no effect of time of day; and, (4) results obtained from reaction time tests did not show decrements in performance—instead there may have been practice effects.]

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Executive Summary

0.1. Objectives of the Study

Fatigue is a subjective state related to sleep deprivation—the more someone is deprived of sleep the more likely that person is to be fatigued. In this study, the relationship between sleep deprivation and the driving performance of commercial motor vehicle (CMV) drivers was explored. Unlike most previous studies of sleep deprivation and driving performance, in this study we investigated the driving performance of each participant in a single experimental session that took place over a twenty-hour period. The objectives of the study were to determine the effect of sleep deprivation on the driving performance, visual performance, and reaction times of CMV drivers.

0.2. Background

Driver fatigue is an important causal factor in many highway crashes—and is of particular concern in the trucking industry where many operators undertake long haul drives with limited amounts of sleep. It has been estimated that 1,200 deaths and 76,000 injuries annually could be attributed to fatigue-related factors and that the cost of these crashes at $12.4 billion per year. Previous studies suggest that fatigue can affect steering performance and speed control. In real world driving studies and in driving simulator studies, steering performance has been found to gradually worsen with time. With regard to speed the picture has been less clear—in a simulation study, drivers were found to increase their speed the longer they drove, although a survey of military truck drivers suggests that when the drivers are fatigued, some drive slower, and others have difficulty estimating their speed correctly.

0.3. Current Study

Twenty CMV drivers, who were recruited with the help of the Minnesota Trucking Association (MTA), participated in the current study. Their driving performance was investigated in a single experimental session that took over a twenty-hour period, during which the participants were continuously kept awake.

0.4. Method

Each participant drove in an advanced driving simulator for approximately one hour on four occasions during the twenty-hour experimental session. The participant drove in the morning (at 9:00 am), the afternoon (at 3:00 pm), the evening (at 9:00 pm) and at night (at 3:00 am). The fixed-base advanced driving simulator used in the study provided a 210-degree forward field-of-view. The simulator also provided a rear view, using a screen mounted behind the vehicle that the driver could see through the vehicle's rear-view mirror, and two LCD panels installed in place of the simulator vehicle's side-view mirrors. The simulated test route was designed with

various features (overpasses and intersections controlled by either traffic lights or stop-signs) and with changes in the speed limits, in order to make the driving experience more like real-word driving and to make it less easy for the participants to predict when they would encounter the various features on the route. It consisted of a long section of four-lane divided highway (with two lanes in each direction with a median between them), a shorter section of two-lane road (with one lanes in each direction), and then another brief section of four-lane divided highway. The virtual position of the simulator vehicle, relative to the scenario through which the participant was driving, was recorded at a rate of 20 Hz throughout each experiment drive. From this record, it was possible to determine the participant's steering performance and the speed at which he or she was driving the vehicle. In addition, three visual performance tests and two reaction time test were administered throughout the testing period. At the end of the fourth drive, each participant was driven to the University of Minnesota's General Clinical Research Center, where he or she was able to sleep for eight hours.

0.5. Results

The following measures of driving performance were collected during each drive—steering instability, mean speed, and stopping behavior at the stop-controlled intersections.

The results indicated that the steering performance of CMV operators was somewhat impaired after they had been kept awake continuously for 20 hours. There was a considerable increase in steering instability from the morning drive (at 9:00 am) to the nighttime drive (which began at 3:00 am). This result—obtained in a driving simulator with participants who were tested in a single experimental session—is consistent with a previous study in which there was as increase in the magnitude of lateral deviations of shift workers after they had worked the night shift when compared to their driving performance after they had a normal night's sleep.

In addition, there was an increase in steering instability during the afternoon drive (at 3:00 pm) compared to the steering instability values obtained in the morning (at 9:00 am) and evening (at 9:00 pm)—suggesting that there was also a diurnal or circadian rhythm effect (sometimes called a postprandial performance dip).

The average driving speed of the participants was lower during the first drive (at 9:00 am) than it was in the third and fourth drives (at 9:00 pm and 3:00 am). There are two possible explanations for this result. The participants may have driven faster because they were fatigued—however, they may have driven faster as they became more familiar with the test route. Unfortunately, it is not possible to decide between these two possibilities.

We examined the effect of time of day on the stopping behavior of the drivers on the approach to the two stop-controlled intersections. Inevitably, as the participants approached the intersections, their mean speed progressively decreased. In addition, for the first drive of the day (at 9:00 am), we found that the participants drove faster earlier on the approach than they did on the subsequent three drives (at 3:00 pm, 9:00 pm, and 3:00 am). This suggests that they adjusted their behavior as they became more familiar with the test route. However, it did not indicate that their stopping behavior was affected by sleep deprivation.

We also determined the distance from the intersections at which each participant began to slow down (i.e., took his/her foot off the accelerator). We found that with the first drive (at 9:00 am) the participants began to slow down when they were closer to the intersection, than they did in the three subsequent drives. The increase in the distance from the intersections at which the participants began to slow down between the first drive (at 9:00 am), and the final drive (at 3:00 am) suggests that there was a learning effect as they became more familiar with the test route—rather than a performance decrement related to sleep deprivation.

We obtained visual performance and reaction time data throughout the experimental session. There were three visual performance tests. First, using a pupillometer, we found that only one measures (the reduction in pupil size *after* the completion of the drives) was statistically significant. After the fourth drive (at 3:00 am), on average, there was less reduction in the pupil size of the participants. However, since there was no significant difference for this measure (or for the other two pupillometer measures) *before* the drives began, we did not find evidence that would indicate that the pupillometer could be used to predict sleep deprivation, fatigue, or the increase in steering instability that occurred for the CMV drivers in the fourth drive (at 3:00 am). Similarly, the data obtained with the other two visual performance tests (a Snellen-equivalent acuity test and a contrast sensitivity test) showed any affect of the time of day at which it was collected.

In addition, the results obtained with the two reaction time tests did not show decrements in performance related to the time of day. The results with both the PVT and the code substitution test, suggested that—to the contrary—performance improved and there may have been practice effects.

0.6. Conclusion

Twenty CMV drivers participated in the study. Their driving performance was investigated in a single experimental session that took over a twenty-hour period, during which the participants were continuously kept awake. The main result of the study was that the steering performance of CMV operators is likely to be somewhat impaired if they are kept awake for an extended period: There was considerable increase in steering instability that occurred between the morning drive, at 9:00 a.m., and the nighttime drive, which began at 3:00 a.m. And this increases in steering instability seems likely to have been produced by sleep deprivation.

There are always issues with the validity of simulator studies. It would be dangerous to replicate the current study using a 59.5-mile (95.8-km) route on real highways while investigating the driving performance of sleep-deprived drivers. However, this study, which was conducted under laboratory condition—but allowed the participants to ingest caffeine and use tobacco as they would in real-world conditions—suggests that the steering performance of professional CMV drivers is likely to be impaired if they are awake from 8:00 or 9:00 am morning until they attempt to drive eighteen or more hours later at 2:00 or 3:00 am in the middle of the night.

Chapter 1: Introduction

1.1. Objectives of the Study

Fatigue is a subjective state that is clearly related to sleep deprivation—the more someone is deprived of sleep the more likely that person is to be fatigued. In this study, the relationship between sleep deprivation and the driving performance of commercial motor vehicle (CMV) drivers was explored. Unlike most previous studies of sleep deprivation and driving performance, we investigated the driving performance of each participant in a single experimental session that took place over a twenty-hour period. The objectives of the study were to determine—

- The effect of sleep deprivation on the driving performance of CMV drivers.
- The effect of sleep deprivation on the visual performance and reaction times of CMV drivers.

1.2. Background

1.2.1. Crash Data and Fatigue

Each year there are huge numbers of crashes on highways in the U.S.A. The most recent available crash data—from "Traffic Safety Facts 2006" (NHTSA, 2006)—shows that there were 5,973,000 crashes on roads in the U.S.A. in 2006; this translates to a crash rate of 198 crashes per 100 million miles traveled (NHTSA, 2006, Table 23, page 44). In 38,588 of these crashes there were fatalities—a fatality crash rate of 1.28 crashes per 100 million miles traveled (NHTSA, 2006, Table 23, page 44).

Driver fatigue is an important causal factor in many highway crashes—and it is of particular concern in the trucking industry in which many operators undertake long haul drives with limited amounts of sleep. However, it is difficult to obtain accurate data on the number of occasions on which fatigue is a factor in fatal crashes—NHTSA (2006, Table 65, page 100) only assigns 1,480 (2.6%) of the 38,588 fatal crashes that occurred in 2006 to the "Drowsy, Fatigued, Ill, or Blackout" category. However, this is certain to be an underestimate. Many fatal crashes involve a single vehicle and, if the driver does not survive, information about his or her state of arousal is completely unknown, or is a matter of conjecture. In these crashes, indications that the driver could have been fatigued are only evident if there is a witness who reports that the driver indicated that he or she was fatigued, or that the driver was slumped over just before the crash. Also, in the case of fatal crashes involving commercial motor vehicle (CMV) drivers, the sleep log may provide information that suggests that the driver was sleep deprived.

Driver fatigue is likely be one of the causal factors in the crashes categorized in two broad categories—(1) Collisions with Fixed Objects and (2) Rollovers. Table 1.1, which is derived from data provided by NHTSA (2006, Table 32, page 54), shows that 43.9% (16,925) of the fatal crashes in 2006 fell into these two categories. As the table shows there were 12,607 collisions with fixed objects (including collisions with poles, posts, culverts, curbs, ditches, guard rails, embankments and bridges) and 4,318 rollovers. The table also shows the number of fatal crashes

that involved collisions with non-fixed objects (i.e., parked vehicles, animals, pedestrians, pedal cyclists, and trains) and with moving vehicles.

Table 1.1: The number and percentage of fatality crashes in 2006 categorized by first harmful event (derived from NHTSA, 2006, Table 32, page 54)

First Harmful Event	Number of Crashes Resulting in Fatalities	Percent of Crashes Resulting in Fatalities
Single Vehicle Collides with Fixed Object	12,607	32.7%
Single Vehicle Rollover	4,318	11.2%
Single Vehicle—Fixed Object *Plus* Rollover	**16,925**	**43.9%**
Single Vehicle Collides with Object that is Not Fixed	6,333	16.4%
Other Single Vehicle Crash	543	1.4%
Collision with Moving Vehicle	14,451	38.1%
Unknown	69	0.2%
Total	**38,588**	

Inevitably, a number of the 16,925 fatal crashes involving Collisions with Fixed Objects and Rollovers that are shown in Table 1.1 will have had a number of contributing factors—including driver inattention, driver misjudgment, excessive speed, alcohol, drugs, and the weather. Nevertheless, it is likely that driver fatigue was involved in a substantial number of them

With regard to crashes involving combination-unit trucks, Rau (1996) estimated that 1,200 deaths and 76,000 injuries annually could be attributed to fatigue-related factors. And Wang, Knipling, and Blinceo (1996) estimated that the cost of these crashes at $12.4 billion per year.

1.2.2. Fatigue and Driving Performance

Fatigue leads to impaired driving performance—because it leads to the withdrawal of the driver's attention from the road and other traffic (Brown, 1994). Several studies have found that fatigue can affect steering performance and speed control.

In real world driving studies, it has been found that steering performance gradually worsens with time, and that decrements in steering performance correlate with drivers' subjective ratings of fatigue (O'Hanlon & Kelley, 1977; Riemersma, Sanders, Wildervanck, & Gaillard, 1977). Steering performance decrements have also been found in driving simulator studies. For example in two simulator studies—one of which required drivers to drive continuously for 2.5 hours (Van der Hulst, Meijman, & Rothengatter, 2001), and the other of which required drivers to drive continuously for three hours (Van Winsum, 1999)—as the drive progressed, steering performance worsened, with steering corrections occurring less frequently but increasing in magnitude. In a third driving simulation study, Desmond (1998) found that fatigue had more

effect on the steering performance of drivers when they drove on straight road segments than when they were driving on curved road segments—she suggested it is more difficult for fatigued drivers to pay attention when the task demands are low (i.e., when they simply have to drive straight) than when the task demands are higher (i.e., when they have to negotiate curves). In a more recent simulator study, Åkerstadt, Peters, Anund and Kecklund (2005), compared the driving behavior of shift workers after they had a normal night's sleep with their performance after they worked the night shift. Åkerstad *et al*. found there was as increase in the magnitude of lateral deviations after the night shift.

With regard to speed, in a simulation study, Hargutt, Hoffmann, Volrath, and Kruger (2000) found that drivers increased their speed the longer they drove. In contrast, when Oron-Gilad and Shinar (2000) surveyed military truck drivers, they found that when the drivers were fatigued, 12% of them indicated that they drove slower, and 14% indicated that they had difficulty estimating their speed correctly. Also, Riemersma, Sanders, Wildervanck, and Gaillard (1977) reported that as drivers became sleepy they exerted less force on the accelerator.

1.2.3. Fatigue Measurement

As already mentioned, fatigue is a subjective state. Useful definitions have been provided by Brown (1993, 1995)—he defines fatigue as "a subjectively experienced disinclination to continue performing the task in hand because of perceived reductions in efficiency"—and Van Dongen and Dinges (2000)—"subjective reports of loss of desire or ability to continue performing." [It is interesting that the latter authors have deemphasized the term "fatigue" in the updated version of their paper (Van Dongen and Dinges (2005), and omitted their definition.] As Belz, Robinson, and Casali (2004) point out "Because fatigue cannot be measured directly, it is often defined operationally in terms of its observable symptoms." When driving is considered, fatigue has been measured by using the following: (1) driving performance measures; (2) physiological measures; (3) behavioral measures; and (4) subjective measures.

Some of these measures have been developed for use in the real world, with the aim of using them either as monitoring devices to continuously monitor driver performance or as checking devices to assess fitness for duty. However, some of the measures can only be used in experimental situations, where greater control is possible. A brief description of these fatigue measures follows.

1.2.3.1. Driving Performance Measures—Driving performance measures can be obtained both in real-world driving and in experimental situations. With driving simulators and instrumented vehicles it is possible to obtain very detailed driving performance data—e.g., steering variability, driving speed, and stopping behavior—similar to those collected in the study reported here.

In addition, there are ongoing efforts to develop devices capable of monitoring aspects of real-world driving performance. For example, it was reported (in Intelligent Vehicle Quarterly, 2000) that a vision-based lane-tracking system, known as SafeTRAC was under development. The system utilized a small windshield-mounted video camera to obtain images of the road ahead. Then, it used proprietary algorithms to process these images to derive the lane position of the vehicle. If the system detects the vehicle weaving excessively, or drifting off the road, an alerting stimulus can be presented to the driver. The SafeTRAC system transmits auditory

alerting messages to the driver. The third generation of SafeTRAC has been released for commercial use (Assitware Technology, 2005).

1.2.3.2. Physiological Measures—Various physiological measures related to fatigue are available. However, many of them are obtrusive. As a result, if they are used to continuously monitor particular behaviors, these measures may directly influence and alter the performance they are attempting to measure.

Belz *et al* (2004) list the following common physiological measure that may be useful in detecting fatigue states: "adrenaline/noradrenaline production, cortocosteriod production, brain electrical activity, eyelid closure, eye position/eye movement, heart rate, and gross body movement." Eyelid closure is perhaps the most useful of these measures for monitoring purposes—because it can be detected in a relatively unobtrusive manor. Probably the most-developed device for continuously monitoring the extent to which a driver is closing his or her eyes is the PERCLOS camera. It provides a measure of the proportion of time per minute that the driver's eyes are at least 80 % closed—hence the name "PERCLOS" (Wierwille, Wreggit, Kirn, Ellsworth, & Fairbanks, 1994). If the driver's eyes are closed for 80 % per minute, or more, an alerting stimulus can be presented to him or her. However, PERCLOS can be difficult to use with those who wear spectacles, and it is difficult to use at night. While perhaps still some way from being used extensively in motor vehicles, recent work suggests that PERCLOS may be of value for monitoring fatigue in commercial airline pilots (Mallis, Neri, Colletti, Oyung, Reduta, Van Dongen, & Dinges, 2004).

Also, a device that examines pupillary responses has been developed in an attempt to provide an off-line measure of fatigue. This device, the EyeCheck™ pupillometer, records a person's pupillary response to a light stimulus, measuring changes in pupil diameter and the rapidity of those changes. Law enforcement officers would find it useful if a device that reliably measures some physical aspect of the driver were available to them. They would then be able to determine whether a driver is too fatigued to drive—it would be analogous to the way in which they currently use a Breathalyzer to test the sobriety of drivers. One objective of the current study was to investigate whether or not the measures obtained with the EyeCheck™ pupillometer are consistently affected by sleep deprivation, and whether or not they are related strongly enough with driving performance so that the device could be used in this way.

1.2.3.3 Behavioral Measures—When people are fatigued, they are more likely to commit errors and their cognitive processes may be slowed. Dual-task paradigms have been used in some driving studies to show performance decrements that can be attributed to fatigue—e.g., Hardee, Dingus, and Wierwillie (1986) obtained impaired performance in auditory and visual secondary tasks performed by sleep-deprived subjects when they were driving in a driving simulator.

Information processing capabilities can also be measured off-line. Wilkinson and Houghton (1982) developed a portable simple visual reaction time (VRT) device that took ten minutes to administer. Using it, they showed that performance scores were lower for subjects deprived of one night's sleep. Dinges and Powell (1985) developed a software system that collected, reduced, edited, transformed, and analyzed the reaction time data obtained with the VRT device. Subsequently, this device became known as the Psychomotor Vigilance Task (PVT). It is often

used in fatigue studies. For example, Powell, Riley, Schechtman, Blumen, Dinges and Guilleminault (1999) used the PVT to compare the reaction times of subjects with sleep-disordered breathing and healthy subjects challenged with alcohol—their Blood Alcohol Concentration (BAC) level was at the legal limit for driving a CMV in California. The reaction time performance of the sleep-disordered subjects was worse than that of the alcohol-challenged subjects. The PVT was one of the tests used by Mallis *et al* (2004). It was also part of the battery of tests used in the current study.

1.2.3.4. Subjective Measures—Finally, a number of subjective measures of fatigue have been developed. Some involve self-report (e.g., Hoddes, Zarcone, Smythe, Phillips, & Dement, 1973), while others use observers trained to use a variety of criteria to recognize changes in a driver's fatigue level (e.g., Wierwillie & Ellsworth, 1994). However, because they are subjective measures there usefulness has been questioned and they were not investigated in the current study.

1.3. Current Study

As mentioned at the beginning of this chapter, the objectives of the current study were to determine—(1) the effect of sleep deprivation on the driving performance of Commercial Motor Vehicle (CMV) drivers, and (2) the effect of sleep deprivation on the visual performance and reaction times of Commercial Motor Vehicle (CMV) drivers.

Twenty CMV drivers participated in the study. We investigated their driving performance in a single experimental session that took place over a twenty-hour period, during which the participants were continuously kept awake. We collected driving performance, visual performance and reaction time data from each of these drivers at various times during the experimental session. Each participant drove in an advanced driving simulator for approximately one hour on four occasions during the twenty-hour test period; he or she drove in the morning, the afternoon, the evening and at night. Driving performance data were collected during each drive. In addition, three visual performance tests and two reaction time test were administered throughout the testing period. [It should be noted that a second study investigating the effect of in-lane rumble strips on sleep deprived CMV drivers was nested within the larger study reported here—Harder and Bloomfield (2005) present a detailed account of this second study.]

1.3.1. Caffeine and Tobacco

In any study requiring participation over an extended period of time, there are issues with substances like caffeine and tobacco—i.e., whether to allow, forbid, or control their use. Those issues had to be confronted in the current study, with its 20-hour experimental session.

1.3.1.1.Caffeine—Juliano and Griffiths (2004) point out that, "Symptoms of caffeine withdrawal have been described in the medical literature for more than 170 years." In their extensive review of caffeine withdrawal, Juliano and Griffiths report that the most common symptoms include the following: headache, tiredness/fatigue, decreased alertness/attentiveness, drowsiness/sleepiness, and difficulty concentrating. They also report that "caffeine-withdrawal symptoms typically emerge 12- 24 hours after abrupt caffeine abstinence."

Only three of the participants selected for this study did not drink coffee or other beverages containing caffeine regularly throughout the day. In this study, the experimental session lasted 20-hours. If we had withheld caffeine from our participants throughout the experimental session, it is likely that some participants would have experienced caffeine withdrawal—and this may have affected their driving performance.

If we had required that all 20 participants ingest the same amount of caffeine at predetermined times during the experimental session, then for participants who never use caffeine as well as for participants who use larger or smaller amount of caffeine than the set amount it is possible that their driving performance would have been affected. Since the objective in this study was to determine the effect of sleep deprivation—not the effect of sleep deprivation plus the effects of caffeine deprivation or excess—we allowed the 20 participants to have access to caffeinated beverages, so that they could drink them as frequently as they usually do.

1.3.1.2. Tobacco—In his review of the effects of abstinence from tobacco, Hughes (2007) discusses common symptoms, which include: anger, anxiety, depression, difficulty concentrating, and impatience. Because most of the studies that Hughes reviews are concerned with the effects of abstinence over a period of weeks, it is not clear what effects would be most likely to manifest themselves in the 20-hour period of the experimental sessions.

Five of the CMV drivers who participated in this study smoke tobacco and one uses smokeless tobacco. If we had not allowed these six participants to use tobacco during the 20-hour experimental period, it is possible that their driving performance may have been affected. And since our objective was to determine the effect of sleep deprivation—not the effect of sleep deprivation plus the effects of abstinence from tobacco—we allowed these six participants too use tobacco. [However, it should be noted that no smoking is allowed in University of Minnesota buildings. Consequently, the participants were not allowed to smoke in the simulator, the subject room, or anywhere else in the building in which the simulator was housed. Between the testing periods the participants were allowed to briefly exit the building if they wanted to use tobacco.

1.3.1.3. Use of Caffeine and Tobacco in this Study—By allowing access to caffeine and tobacco for participants who usually drink caffeinated beverages and/or usually smoke tobacco, we more closely reproduced the conditions in the real world in which the CMV drivers operate everyday.

Chapter 2: Method

2.1. Participants

The twenty CMV drivers who took part in the main study had experience with long haul operations. They were recruited with the help of the Minnesota Trucking Association (MTA). The MTA informed their members by email that a study of the effects of fatigue on driving was to be conducted at the University of Minnesota. Drivers who were interested in the study called the University and were screened, using a series of screening questions (presented in Appendix A). Potential participants were excluded from the study if they suffered from migraines or severe tension headaches, experienced motion sickness in automobiles, airplanes, or on amusement park rides, if they felt queasy at IMAX presentations, if they had been diagnosed with a sleep disorder, and/or if they were pregnant or breast feeding. In addition, each potential participant took part in a screening visit that occurred six or seven days before the main study. During this screening visit, he or she drove for approximately ten minutes in the driving simulator. [One participant felt queasy during this drive and stopped before the end of the ten minutes. He did not take part in the main study.] The selected participants were between the ages of 25 and 60 years, had 20/20 vision (with corrective lenses, if necessary), a current driver's license, and at least three years of driving experience. Participants were paid $600 for taking part in the study.

During the main experiment, the participants drove in the simulator on four occasions—fourteen participants drove at 9:00 am, 3:00 pm, 9:00 pm, and 3:00 am; and six drove at 8:00 am, 2:00 pm, 8:00 pm, and 2:00 am. At the end of the fourth drive, each participant was driven to the University of Minnesota's General Clinical Research Center, where he or she was able to sleep for eight hours. Before the experiment began, the participants were informed that if, at any time, they did not want to continue the experiment they could withdraw. If they withdrew before 11:30 pm (if they started at 8:30 am) or before 10:30 pm (if they started at 7:30 am), then they could simply leave. However, for safety reasons, if the participants withdrew after 11:30 pm (if they started at 8:30 am) or 10:30 pm (if they started at 7:30 am), they would be escorted to the General Clinical Research Center, where they would be able to sleep for eight hours. Before the experiment began, the participants were informed that if they withdrew from the study they would receive $10 for each hour that they participated in the study (including the time they were sleeping). The study protocol was reviewed and approved by both the University of Minnesota's IRB and by the General Clinical Research Center's IRB.

[In addition to the twenty participants from whom we obtained data, it should be noted that five other CMV drivers went through the experimental protocol. One of these drivers was a pilot subject used to test the procedures. Data from the other four drivers was not used. Of these, one missed so much sleep the day before participating in the study, that his driving performance data were atypical. The driving performance data from the remaining three drivers were lost—and could not be recovered—when a change was made to the simulator software during the weekend that they were tested. These four drivers were replaced.]

2.2. Experimental Design

A within subjects experimental design was used. Each of the participants drove the test route of 59.53 miles (95.80 km) four times. [Please note, throughout this report, the following conversion rates are used: 1 mile = 1.609347 km; 1 ft = 0.3048 m, and 1 in = 2.54 cm.] The four times that the participants drove were in the morning, afternoon, evening, and at night. Before and after each drive, a pupillometer test was administered to the participants. In addition, between drives the followings tests were administered: a Snellen-equivalent acuity test, a contrast sensitivity test, the PVT, and a code substitution test. These tests are described in more detail in section 2.6 below.

2.3. The Driving Simulator

We use a fixed-base advanced driving simulator for the study. The key components of the simulator were as follows:

2.3.1. Simulator Vehicle
The simulator vehicle was a full-body 2002 Saturn SC1 coupe.

2.3.2. Simulator Visuals
There was a 210-degree forward field-of-view—provided by five flat-panel screens each of which was 4.7-ft (1.43-m) high by 6.5-ft (1.98-m) wide. There was a central flat panel in front of the simulator vehicle. The center of this panel was aligned with the line of sight of the driver in the simulator vehicle. Two intermediate panels flanked the central panel, to the left and right. These two intermediate panels were set at 138-degrees to the central panel. Then there were two outer panels—one on the right, the other on the left—that were set at 138-degrees to the intermediate panels. The base of all five flat-panel screens was elevated 1.33 ft (0.06 m) above the floor. Five projectors were used to project a coordinated, high-fidelity, virtual environment onto the five flat-panels comprising the 210-degree forward field-of-view. The simulator provided rear-view imagery in two ways. First, there was a 10-ft (3.05-m) high by 7.5-ft (2.29-m) wide screen—mounted behind the vehicle—that the driver could see through the vehicle's rear-view mirror. Second, two 5-inch (12.7 cm) LCD panels were installed in place of the simulator vehicle's side-view mirrors. Coordinated imagery was presented on the five-forward and the three rear-view channels.

2.3.3. Simulator Vehicle Controls
The simulator vehicle's controls were equipped with sensors that relayed to the driving simulator computer the participant's inputs to the steering wheel, transmission, and accelerator and brake pedals. The simulator computer provided a real-time interface with the virtual environment. Force feedback was applied to the steering wheel, using a high-torque motor attached to the steering column. A vacuum assist pump was connected to the brake pedal in order to simulate realistic braking. The simulator vehicle was equipped with an automatic transmission interface, which was functional and was controlled by the simulator computer.

2.3.4. Simulator Sound System
Road and traffic noise, and the simulator vehicle's engine sounds were delivered through four speakers placed around the vehicle's exterior near the base of the five panels that comprised the forward view. Each speaker received independent inputs from the simulator's 3D sound generation system. Low-frequency sounds were delivered using a ten-inch subwoofer located inside the simulator vehicle's engine compartment. If necessary, the experimenter could communicate with each participant via a dedicated intercom system that made use of four speakers installed in the simulator vehicle's factory speaker locations.

2.3.5. Simulator Vehicle Movement
The simulator was a fixed-base simulator. However, a bass shaker mounted to the underside of the vehicle's frame provided low-frequency vibration.

2.3.6. Data Recording
The virtual position of the simulator vehicle, relative to the scenario that each participant was driving, was recorded at a rate of 20 Hz throughout each experiment drive. From this record, it was possible to determine the participant's steering performance and the speed at which he or she was driving the vehicle. In addition, three micro-video cameras positioned in the cab of the simulator vehicle were used to record (i) the participant's face, (ii) his or her foot position, and (iii) his or her steering wheel responses throughout the course of each experimental session. A video display at the experimenter's station enabled the experimenter to monitor the participant throughout each session.

2.4. The Test Route

2.4.1. Test Route Features and Distances
The participants drove for 59.53 miles (95.80 km) on the route shown in Figure 2.1. The route consisted of a long section of four-lane divided highway (with two lanes in each direction with a median between them), a shorter section of two-lane road (with one lane in each direction), and then another brief section of four-lane divided highway. The test route was designed with the various features at different distances and with changes in the speed limits in order to make the driving experience more like real-word driving and to make it less easy for the participants to predict when they would encounter the various features on the route.

Table 2.1, which follows Figure 2.1, presents a key to the features in Figure 2.1 and, in addition, indicates the distances between the features and the distance of each feature from the start of the route.

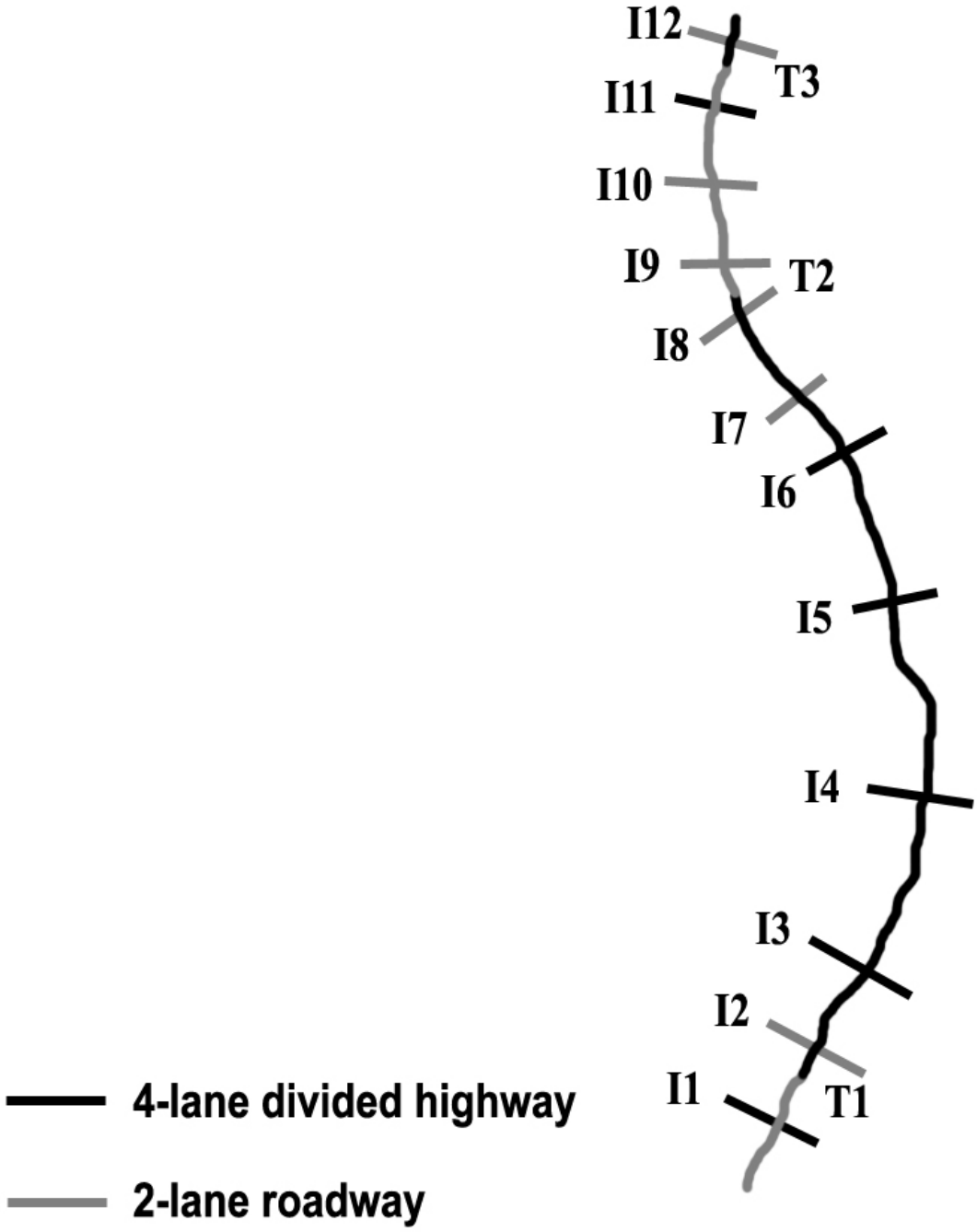

Figure 2.1: The test route: Key—T = Transition points at which the road type changed; I = Intersections

Table 2.1: Key to the features indicted in Figure 2.1 [T = Transition points at which the road type changed; I = Intersections]—with the distance of each feature from the previous feature and from the start of the drive

Key	Feature	Distance from Previous Feature	Distance from Start
T1	Start of drive	0	0
I2	1st traffic light	3,153 m (1.96 miles)	3,153 m (1.96 miles)
I3	overpass	7,618 m (4.73 miles)	10,771 m (6.89 miles)
I4	overpass	16,204 m (10.07 miles)	26,975 m (16.76 miles)
I5	overpass	17,338 m (10.77 miles)	44,313 m (27.53 miles)
I6	overpass	13,147 m (8.17 miles)	57,460 m (35.70 miles)
I7	overpass	6,007 m (3.73 miles)	63,467 m (39.44miles)
I8	2nd traffic light	9,029 m (5.61 miles)	72,496 m (45.05 miles)
T2	End 4-lane divided/ start 2-lane highway	1,629 m (1.01 miles)	74,125 m (46.06 miles)
I9	3rd traffic light	2,886 m (1.79 miles)	77,011 m (47.85 miles)
I10	Stop—with rumble	6,563 m (4.08 miles)	83,574 m (51.93 miles)
I11	Stop—no rumble	7,061 m (4.39 miles)	90,635 m (56.32 miles)
T3	End 2-lane/ start 4-lane divided highway	3,515 m (2.18 miles)	94,150 m (58.50 miles)
I12	End of drive	1,653 m (1.03 miles)	95,803 m (59.53 miles)

Each participant started at the first transition point (T1) shown in Figure 2.1 and drove for a total of 59.5 miles (95.80 km). Each participant began by driving on a four-lane divided highway for 46.06 miles (74.13 km). He or she encountered a traffic light at intersection I2, 1.96 miles (3.15 km) from the start of the drive. Then, there were overpasses, with exit and entry ramps, at points I3, I4, I5, I6, and I7, before the participant reached a second traffic light at I8—45.05 miles (72.50 km) from the start of the drive.

After the four-lane divided highway ended at T2, the participant drove on a section of two-lane road. The two-lane section of the route was 12.44 miles (20.03 km) in length. Each participant encountered a third traffic light at I9—this occurred after he or she had driven on the two-lane road for 1.79 miles (2.89 km) and 47.85 miles (77.01 km) from the start of the test route—and two stop-sign controlled intersections. It should be noted that the second of these stop-controlled intersections, at I10, had rumble strips as well as stop signs. Intersection I10 occurred 5.87 miles (9.45 km) into the two-lane section of the route and 51.93 miles (83.57 km) from the start of the drive. The second of the stop-controlled intersections, at I11, did not have rumble strips signs—it occurred 10.26 miles (16.51 km) into the two-lane section and or 56.33 miles (90.64 km) from the start of the drive.

Finally, there was a second brief section of four-lane divided highway. Each participant drove on this section for 1.03 miles (1.65 km)—at which point there was another intersection, I12. The participant was asked to stop just before intersection I12, having driven 59.53 miles (95.80 km) from the start of the drive.

2.4.2. Test Route Speed Limits
At the start of the test route, the speed limit was 55 mph. The limit increased to 65 mph between the first intersection (I1) and the second intersection (I2). The speed limit was reduced to 55 mph again, between the sixth intersection (I6) and the seventh (I7). The speed limit changed for the last time, increasing to 65 mph, near the end of the route, between eleventh intersection (I11) and the twelfth intersection (I12).

2.5. Driving Performance Measures

The following measures of driving performance were collected in this experiment—

- Steering instability
- Average speed
- Stopping behavior at stop-controlled intersections.

The first two of these driving performance measures—steering instability, and average speed—were collected throughout each drive. The stopping behavior data were collected on the approach to the two stop-controlled intersections.

2.5.1. Steering Instability
Initially, researchers using driving simulators (e.g., McLean & Wierwillie, 1975; Wierwillie & Guttman, 1978) measured steering performance in relation to the center of the lane—i.e., in terms of deviation of the driver's line of travel from the center of the lane. This made sense because the earliest simulators—like that used by Wierwillie and his colleagues—used a single line to represent the route that their participants were asked to follow. Subsequently, simulators improved greatly and researchers were able to use lane markings instead of a single line in the center of the lane. However, many researchers continued to measure steering performance by determining the deviation of the driver's line of travel from the, now invisible, center of the lane. Unfortunately, using deviation from the center of the lane as the measure of steering performance leads to treating drivers who hold firmly to a course which is consistently to the right, or the left, of the invisible line as if they have poor steering performance. They are not distinguished from drivers who weave from one side of the lane to the other.

In order to remove this bias against drivers who hold firmly to a course that is consistently off the line in the center of the lane, Bloomfield and Carroll (1996) suggested that steering instability should be used as the measure of steering performance. This measure has been used in a number of studies—e.g., including Bloomfield, Levitan, Grant, Brown, and Hankey (1998), and Weiler, Bloomfield, Woodworth, Grant, Layton, Brown, McKenzie, Baker, and Watson (2000). This was the measure of steering performance used in the current experiment.

For the current study steering instability was determined in the following way. First, the 59.53-miles (95.80-km) test route was divided into seven segments. [Two brief sections of road at the beginning and the end of the test route were not included in the segmentation scheme—the first was the1.96-mile (3.15-km) section from T1 to the traffic-light controlled intersection at I2 at the start of the test route; while the second was the 3.21-mile (5.19-km) section from the second stop-controlled intersection at I11 to the end of the route]. The seven segments for which the

data were analyzed are shown in Table 2.2. The table shows the start and end point of each segment, the distance between the start and end points of each segment, and the road type (4-lane divided highway or 2-lane/2-way highway) of each segment. In addition, the table shows the speed limit in each of the seven segments—it should be noted that in segment #1 the speed limit changed from 55 mph to 65 mph; that in segment #2 through segment #5 the speed limit was 65 mph; that in segment #6 the speed limit changed from 65 mph to 55 mph, and that in segment #7 the speed limit was 55 mph.

As mentioned earlier, the test route was designed with various features at different distances and with changes in speed limits in order to make the simulated driving experience more like real-word driving—so that it would be harder for the participants to predict when they would encounter the various features on the route. Because of this, the segments, which were defined in terms of the features for analysis purposes, were of unequal length and had varying speed limits—and we expected that there would be differences in driving performance in these segments. However, our focus was on whether or not there would be differences between the four drives that occurred at different times throughout the twenty-hour test period.

Table 2.2: Test route segmentation scheme

Segment	Between	Distance	Road Type	Speed Limit
#1	I2 & I3	7,618 m (4.73 miles)	4-lane divided	55 mph to 65 mph
#2	I3 & I4	16,204 m (10.07 miles)	4-lane divided	65 mph
#3	I4 & I5	17,338 m (10.77 miles)	4-lane divided	65 mph
#4	I5 & I6	13,147 m (8.17 miles)	4-lane divided	65 mph
#5	I6 & I7	6,007 m (3.73 miles)	4-lane divided	65 mph
#6	I7 & T2	10,658 m (6.62 miles)	4-lane divided	65 mph to 55 mph
#7	T2 & I11	16,510 m (10.26 miles)*	2-lane	55 mph

[*Note: two sub-segments of 300 m (984.3 ft) before the two stop-controlled intersections at I10 and I11 were not included in Segment 7—only stopping behavior was analyzed in these two sub-segments. Also, a sub-segment of 100 m (328.1 ft) after the stop-controlled intersection at I10 was not included, as this included the distance in which participants accelerated back to their cruising speed.]

Lane position data were obtained at a rate of 20 Hz. The line of best fit for the lane position data for each participant and each drive in each of the seven segments shown in Table 2.2 was calculated using the method of least squares. Then, the standard deviation around the line of best fit was determined. This standard deviation is the measure of steering instability: the higher the steering instability (i.e., the greater the standard deviation around the line of best fit), the more the driver is weaving back and forth; and the lower the steering instability, the more smoothly the driver is driving and keeping to the line of best fit. Steering instability (i.e., the standard

deviation of mean lane position) was calculated for each participant as he or she drove each segment in Table 2.2 in each of the four drives.

2.5.2. Average Speed
For each drive, the average speed at which each participant drove in each of the seven segments shown in Table 2.2 was determined.

2.5.3. Stopping Behavior
In order to examine the stopping behavior of the participants at the stop-controlled intersections on each of the four drives, another segmentation scheme was employed. We divided the final 418 meters (1,371.4 ft) of the approach to each of these two intersections into fifteen segments—there were two 50-meter (164-foot) segments, twelve 25-meter (82-foot) segments, and one 18-meter (59-foot) segment. The segmentation scheme is shown in Table 2.3.

Table 2.3: Segmentation of approach to stop-controlled intersections

Segment Number	Segment location relative to the edge line at the intersection
1	418-368 meters (1,371-1207 feet)
2	368-318 meters (1207-1043 feet)
3	318-293 meters (1043-961 feet)
4	293-268 meters (961-879 feet
5	268-243 meters (879-797 feet)
6	243-218 meters (797-715 feet)
7	218-193 meters (715-633 feet
8	193-168 meters (633-551 feet)
9	168-143 meters (551-469 feet)
10	143-118 meters (469-387 feet)
11	118-93 meters (387-305 feet)
12	93-68 meters (305-223 feet)
13	68-43 meters (223-141 feet)
14	43-18 meters (141-59 feet)
15	18-0 meters (59-0 feet)

2.6. Test Battery

In addition to driving four times in the driving simulator, several tests were administered to each participant. The pupillometer was used eight times—before and after each of the four test drives. The remaining four tests were presented four times—after the first drive, and before the second, third, and fourth drives. These tests are described below.

2.6.1. Pupillometer Test
The EyeCheck™ pupillometer outwardly looks like a pair of binoculars; it works in the following way. A beam of infrared light is projected into the participant's pupil and the device measures the amount of light that is reflected back from the retina. From this, it is possible to

calculate the size of the pupil. When the pupillometer test was administered in this study, the participant looked into the device and fixated on a red cross. After fixating on this cross for 30 seconds, a controlled green flash was directed into his or her pupil. The green light was reflected back from the participant's retina and the device recorded the resultant change in pupil size and the rapidity of that change. The following measures were collected with the pupillometer—(1) the time in milliseconds from the beginning of the flash to the moment that the pupil started to constrict (defined by the manufacturer of the device as TTI), (2) the time in milliseconds until full constriction occurred (defined as TTM), and (3) the reduction in pupil size (defined as RA%). Each participant was tested with the pupillometer immediately before and after each of the four drives.

2.6.2. Snellen-Equivalent Acuity

A Ferree and Rand chart was used to determine whether there was any change in the visual acuity of the participants over the course of the main experimental session. On the chart there are a series of black circles that are systematically reduced in size from line to line. There was a break in each of these black circles. The break appeared in one of the following eight locations—(1) top; (2) top left; (3) left; (4) bottom left; (5) bottom; (6) bottom right; (7) right; and (8) top right. The participant's task was to state where the break occurred in each circle. Each participant was tested four times with the Ferree and Rand chart—(1) after the first drive in the simulator; (2) before the second drive; (3) before the third drive; and (4) before the fourth drive.

2.6.3. Contrast Sensitivity

A Pelli-Robson chart was used measure any change in contrast sensitivity that might have occurred for the participants throughout the course of the main experimental session. On both sides of this chart there are a series of large letters of different shades of gray. There are six letters per line. The contrast of each letter against the white background on which it is presented is systematically reduced from the top left of the chart to the bottom right. The participant's task was read the chart, naming each of the letters until he or she could no longer detect them. Each participant was tested four times with the Pelli-Robson chart—(1) after the first drive in the simulator; (2) before the second drive; (3) before the third drive; and (4) before the fourth drive. One side of the chart used for the first and third tests, with the other side used for the second and fourth tests.

2.6.4. Psychomotor Vigilance Test (PVT)

The PVT was used to determine whether there were changes in the reaction times of the participants over the course of the main study. When the PVT was administered the participant held the PVT device and looked at its small screen. A trial began whenever red numbers appeared on the screen. The numbers on the screen rapidly increased—they provided a count of the number of milliseconds since the onset of the trial. The participant's task was to press a response button as quickly as possible. The response time was recorded. The interval between the end of one trial and the start of the next was randomly varied. Two measures are typically obtained with the PVT. One is the number of lapses (i.e., reaction times longer than 0.5 seconds) in a test session. Lapses are rare and, usually, are not an indicator of impairment until a subject has been sleep deprived for over 24-hours—so this measure was not used in this study. However, the second PVT measure, the average reaction time of the fastest ten percent of the

responses in a test session, was used in the study. The PVT test took ten minutes to administer. Each participant was tested with it four times—(1) after the first drive in the simulator; (2) before the second drive; (3) before the third drive; and (4) before the fourth drive.

2.6.5. Code Substitution Test

The code substitution test was administered using a computer. To take the test, each participant began by looking at the computer screen. At the top of the screen, there was a row of letters. Immediately below each letter, there was a number in parentheses. Lower on the screen there was a second row of letters; and, immediately below each of these letters there were parentheses with nothing between them. The participant's task was (1) to look at each letter in this second row; (2) to find that letter in the top row and see which number in parenthesis was paired with it; then, (3) using the computer number pad, to insert the paired number in the parentheses underneath the letter in the second row. As soon as the participant did this, he or she moved on to the next letter in the second row and repeated the procedure. When the participant finished adding numbers below all the letters in the second row, the screen was cleared, and a different set of paired letters and numbers appeared in the top row—the letters in the second row also changed. The code substitution test took ten minutes, and the number of correct responses for each participant in each ten-minute testing period was determined. Each participant was tested four times—(1) after the first drive, (2) before the second drive, (3) before the third drive, and (4) before the fourth drive.

2.7. Experimental Procedure

The experimental procedure began with had an initial contact made by telephone. This was followed by a screening visit. Then approximately a week later the main study occurred. These three stages are detailed below.

2.7.1. Initial Contact

First, the Minnesota Trucking Association informed trucking companies that are part of the association that a study of the effects of fatigue was to be conducted. Potential participants contacted us, by phone or in a few cases by email. They were given information about the study—particularly its length. If they were interested in participating, they were asked a series of screening questions. Then, each of those who were eligible for the study and who were able to fit the study into their schedule, made appointments to visit the facility for the screening visit and the main study.

2.7.2. Screening Visit

The screening visit took place approximately one week before the main study. Each potential participant was asked to read and sign a consent form for the screening visit and was again asked the series of screening questions. Then, he or she drove for approximately ten minutes in the driving simulator. [As mentioned earlier, one participant felt queasy during the screening drive, did not complete the drive, and did not take part in the main study.] After the test drive in the simulator, the other participants who were screened were given an Actiwatch and asked to wear it until they returned for the main study. They were also asked to fill out a sleep diary each day before the main study. Then the session, which took approximately 40 minutes, ended.

2.7.3. Main Study

The main study was conducted on Fridays, Saturdays, or Sundays. It was run on 18 days. On eleven of these days there was one participant in the main study. Of the eleven participants who were run alone, one was the pilot participant, and another was one of the three participants whose data could not be recovered—data from the other nine participants are reported here. On the other seven days that the main study was conducted, there were two participants, whose schedules were staggered by one hour. The fourteen participants who participated on these days include eleven participants from whom data is reported as well as two of the three participants whose data could not be recovered and the participant whose data were excluded because they were atypical on all of his drives.

On the days when there was only one participant, the session began at 8:30 am. On the days when there were two participants, the first participant began at 7:30 am, with the second following at 8:30 am—the test procedure was the same for both participants, except for the one-hour time shift.

Fourteen of the twenty participants drove at 9:00 am, 3:00 pm, 9:00 pm, and 3:00 am; while the remaining six participants drove at 8:00 am, 2:00 pm, 8:00 pm, and 2:00 am.

The schedule followed by the participant is described below. The schedule described is for the fourteen participants who arrived at 8:30 am. For the six participants who arrived at 7:30 am, their entire schedule was one hour earlier than the times listed below.

8:30 am—The participant arrived at the simulator facility and gave an experimenter the sleep diary and the Actiwatch. Then, the participant read and signed a consent form for the main study.

8:40 am—The participant was tested with the pupillometer.

8:50 am—The participant took a practice drive in the driving simulator. During this practice drive, which lasted approximately ten minutes, an experimenter sat in the vehicle with the participant. The drive began on a 4-lane divided highway, and then transitioned to a 2-lane road. During the practice drive, the experimenter asked the participant to switch lanes, from right to left, and back again, three times. Also during the drive, the experimenter instructed the participant to practice stopping in a normal fashion and to make an emergency stop.

9:00 am—The experimenter got out of the simulator vehicle. Then, the first test drive began. The participant was asked to drive the test route as he or she “normally would.”

10:00 am—The first test drive ended. The participant got out of the simulator vehicle. The participant was tested with the pupillometer and then with the other tests in the test battery, in the following order—the contrast sensitivity test; the code substitution test; the PVT; and the Snellen-equivalent acuity test.

12:00 noon—Lunch was provided for the participant from a local restaurant. [Typically, the participant walked with an experimenter to the restaurant, then brought the meal back to the subject room in which they spent most of their time between testing periods.]

2:30 pm—An experimenter administered the battery of tests to the participant in the following order—the Snellen-equivalent acuity test; the PVT; the code substitution test; the contrast sensitivity test; and then the pupillometer.

3:00 pm—The second test drive began. Again, the participant was asked to drive the test route as he or she "normally would."

4:00 pm—The second test drive ended. The participant got out of the simulator vehicle, and then was tested with the pupillometer.

6:00 pm—Dinner was provided for the participant from a local restaurant. [Again typically, the participant walked with an experimenter to the restaurant, and brought the meal back to the subject room.]

8:30 pm—An experimenter administered the battery of tests to the participant in the following order—the Snellen-equivalent acuity test; the PVT; the code substitution test; the contrast sensitivity test; and the pupillometer test.

9:00 pm—The third test drive began, with the participant asked to drive as he or she "normally would."

10:00 pm—At the end of the third test drive, the participant was tested with the pupillometer.

12:00 midnight—Snacks were provided for the participant in the subject room.

2:30 am—Once again, an experimenter administered the battery of tests to the participant in the following order—the Snellen-equivalent acuity test; the PVT; the code substitution test; the contrast sensitivity test; and the pupillometer test.

3:00 am—The fourth test drive began, with the participant asked to drive as he or she "normally would."

4:00 am—At the end of the fourth test drive, the participant was tested with the pupillometer. Then, the participant was driven to the General Clinical Research Center.

12:30 pm—The participant was discharged from the GCRC, and driven home by a friend, by a relative, or by taxi.

Chapter 3: Results and Discussion

3.1. Experimental Measures

In this study of the effects of sleep deprivation on CMV drivers, several performance measures were collected. Throughout each of the four one-hour drives occurring throughout the day, the virtual position of the simulator vehicle relative to the route was recorded at a rate of 20 Hz. In addition to collecting driving performance data, visual performance data were collected with the pupillometer, the contrast sensitivity test and the Snellen-equivalent acuity test. Also, reaction data were obtained when the PVT and the code substitution test were administered. The results obtained are discussed in the following subsections of this report.

3.2. Driving Performance Data

3.2.1. Steering Performance

Steering performance was measured by determining the steering instability for each participant as he or she drove at various times of the day (i.e., at 9:00 am, 3:00 pm, 9:00 pm and 3:00 am). For analysis purposes, the test route was divided into seven segments, as mentioned earlier in the Method Section (details of the segments are shown in Table 2.2). An analysis of variance (ANOVA) was conducted on the steering instability data obtained in these seven segments of the test route. The results of this ANOVA are summarized in Table 3.1.

Table 3.1: Summary of ANOVA conducted on steering instability data

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F-value	p-value
Subjects	18	0.970	0.054		
Time of Day	3	0.297	0.099	10.298	**<0.0001**
Error Term I (Time of Day X Subjects)	54	0.519	0.010		
Route Segments	6	0.392	0.065	13.129	**<0.0001**
Error Term II (Route Segments X Subjects)	108	0.538	0.005		
Interaction: (Time of Day X Segments)	18	0.073	0.004	1.374	0.1420
Error Term III (Time of Day X Route Segments X Subjects)	324	0.961	0.003		

Table 3.1 indicates that there were two statistically significant main effects. First, the time of day at which the drive occurred affected steering instability. Also, as expected, there were differences in the steering instability in the seven route segments.

3.2.1.1. Time of Day—The effect of the time of day on steering instability is illustrated in Figure 3.1.

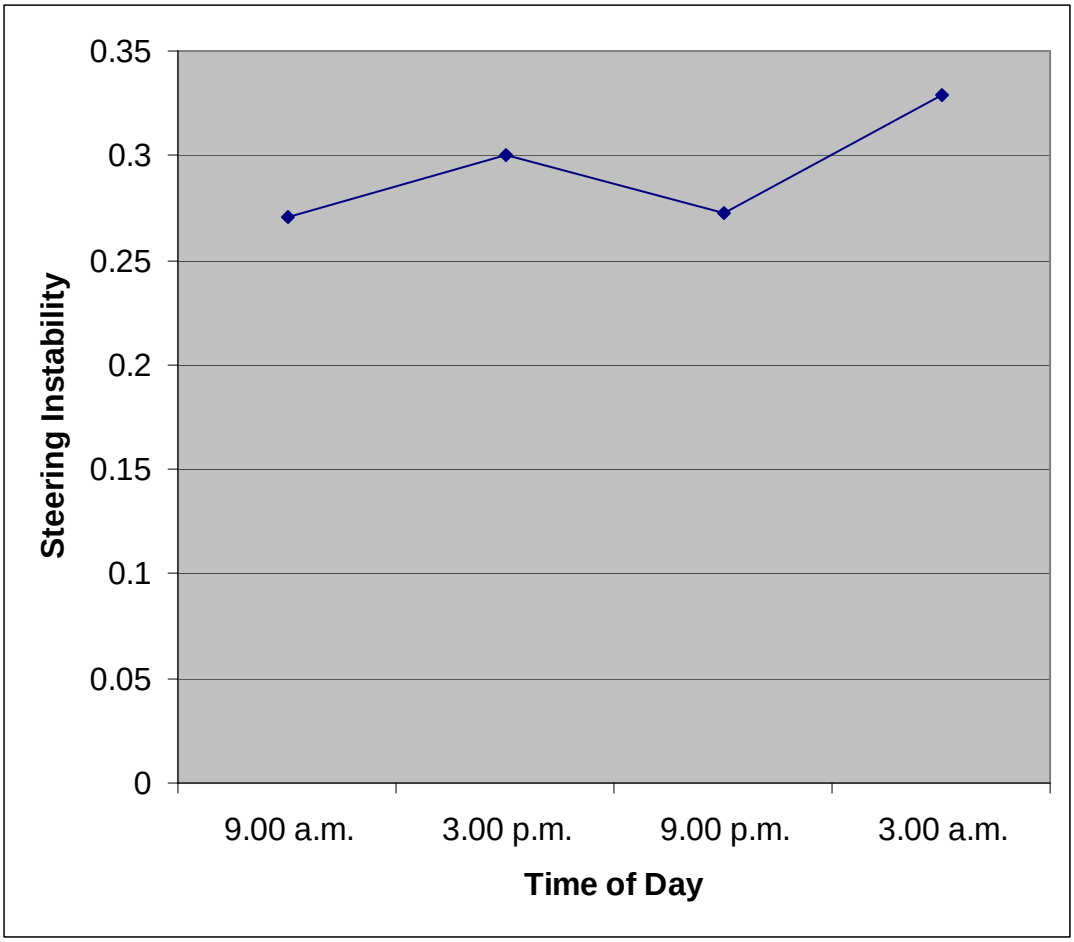

Figure 3.1: Average variability in steering performance for the four drives

As Figure 3.1 shows, there was less steering instability at 9:00 am in the morning, during the first drive, and at 9:00 pm in the evening, during the third drive, than there was at 3:00 pm, in the afternoon, during the second drive, or at 3:00 am in the night, during the fourth drive. A Tukey-Kramer test was conducted on these data *post-hoc*—it indicted that there were statistically significant differences in steering instability between the 9:00 am drive and the 3:00 am drive and between the 9:00 pm drive and the 3:00 am drive. These differences seem very likely to be to be the result of sleep deprivation. Also, before or after the fourth drive, a number of the participants mentioned that while they were prepared to drive in the simulator they felt so tired that they would not have driven a real vehicle on real roads. [When the experimenters heard this they noted what the participants said, but made no comment and, importantly, made no attempt to coerce the drivers into driving the fourth drive.]

The higher steering instability value obtained in the afternoon drive, at 3:00 pm, just missed being significantly different (with the Tukey-Kramer test) from the steering instability values

that were obtained at 9:00 am and 9:00 pm—however, this higher value is consistent with there being a diurnal or circadian rhythm effect. This effect, sometimes called a postprandial performance dip, is not always found—in some studies, as Van Dongen and Dinges (2005) point out, it can masked by practice, ceiling or floor effects.

The finding that there were statistically significant differences in steering instability between both the 9:00 am drive and the 9:00 pm drive and the final drive of the experimental session, at 3:00 am, is consistent with the data reported by Åkerstad *et al*. The participants in the study conducted by Åkerstad *et al*. were not tested in a single experimental session, as were the participants in the study reported here. Instead, Åkerstad *et al*. found there was as increase in the magnitude of lateral deviations of shift workers after they worked the night shift as compared to their driving performance after they had a normal night's sleep.

3.2.1.2. Effect of Route Segment—The effect of the route segments on steering instability is illustrated in Figure 3.2.

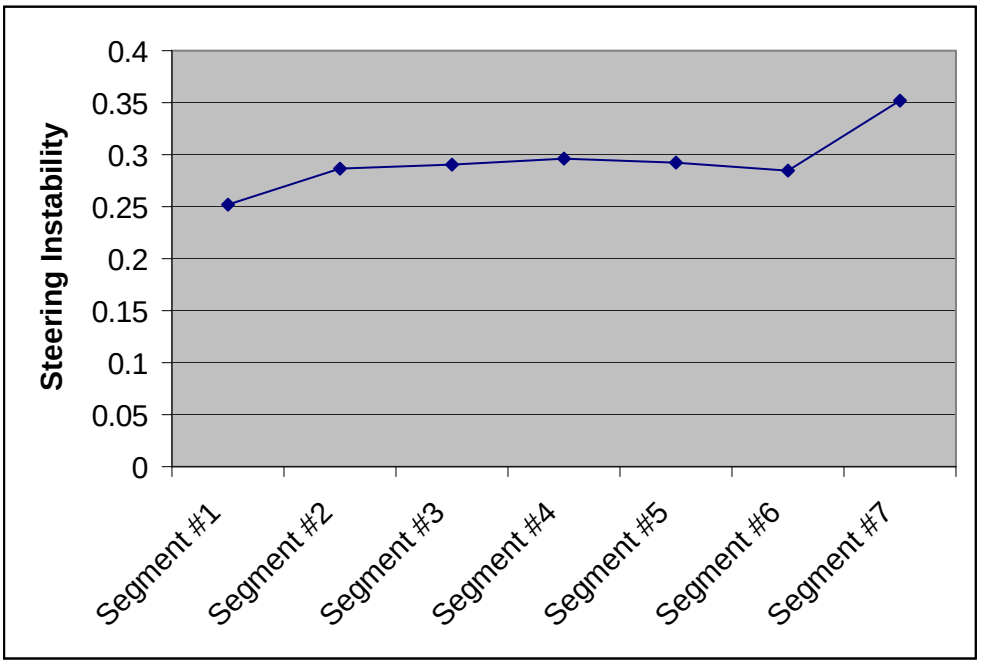

Figure 3.2: Average variability in steering performance in the seven segments of the test route

Figure 3.2 shows that there was more steering instability in the final road segment than in the previous six segments. As mentioned earlier, in the current study the segments were of unequal length and had varying speed limits—and this may have produced the increase in steering instability in the seventh road segment. However, the increase in steering instability shown in Figure 3.2 is consistent with the findings of Van der Hulst, Meijman, and Rothengatter (2001), whose participants drove continuously for 2.5 hours, and of Van Winsum (1999), whose

participants drove continuously for 2.5 hours. In both of those simulator studies, as the drive progressed, steering performance worsened.

3.2.2. Driving Speed

We determined the average driving speed of each participant in the seven segments of the test route, in each of their four drives. An ANOVA was conducted on these speed data. The summary of the results of this ANOVA is presented in Table 3.2.

Table 3.2: Summary of ANOVA conducted on mean speed data

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F-value	p-value
Subjects	18	24,570.390	1,365.022		
Time of Day	3	1,682.017	560.672	2.107	0.1101
Error Term I (Time of Day X Subjects)	54	14,372.704	266.161		
Route Segments	6	14,177.467	2,362.911	124.481	**<0.0001**
Error Term II (Route Segments X Subjects)	108	2,050.071	18.982		
Interaction: Time of Day X Segments	18	266.175	14.787	1.723	**0.0342**
Error Term III (Time of Day X Route Segments X Subjects)	324	2,870.457	8.582		

Table 3.2 indicates that the route segments had a statistically significant effect on driving speed and that, in addition, there was a statistically significant interaction between route segments and the time of day. These effects are illustrated in Figure 3.3.

3.2.2.1. Effect of Time of Day—Inspection of Figure 3.3, shows that for the all seven road segments, the average driving speed was lower in the first drive than in the third drive and fourth drives. There are at least two possible explanations for this finding. The participants may have driven faster because they were fatigued—which would be consistent with the results of the study by Hargutt, Hoffmann, Volrath, and Kruger (2000) or, alternatively, they may have driven faster as they became more familiar with the test route. Unfortunately, we have no way of distinuguishing between these two possibilities.

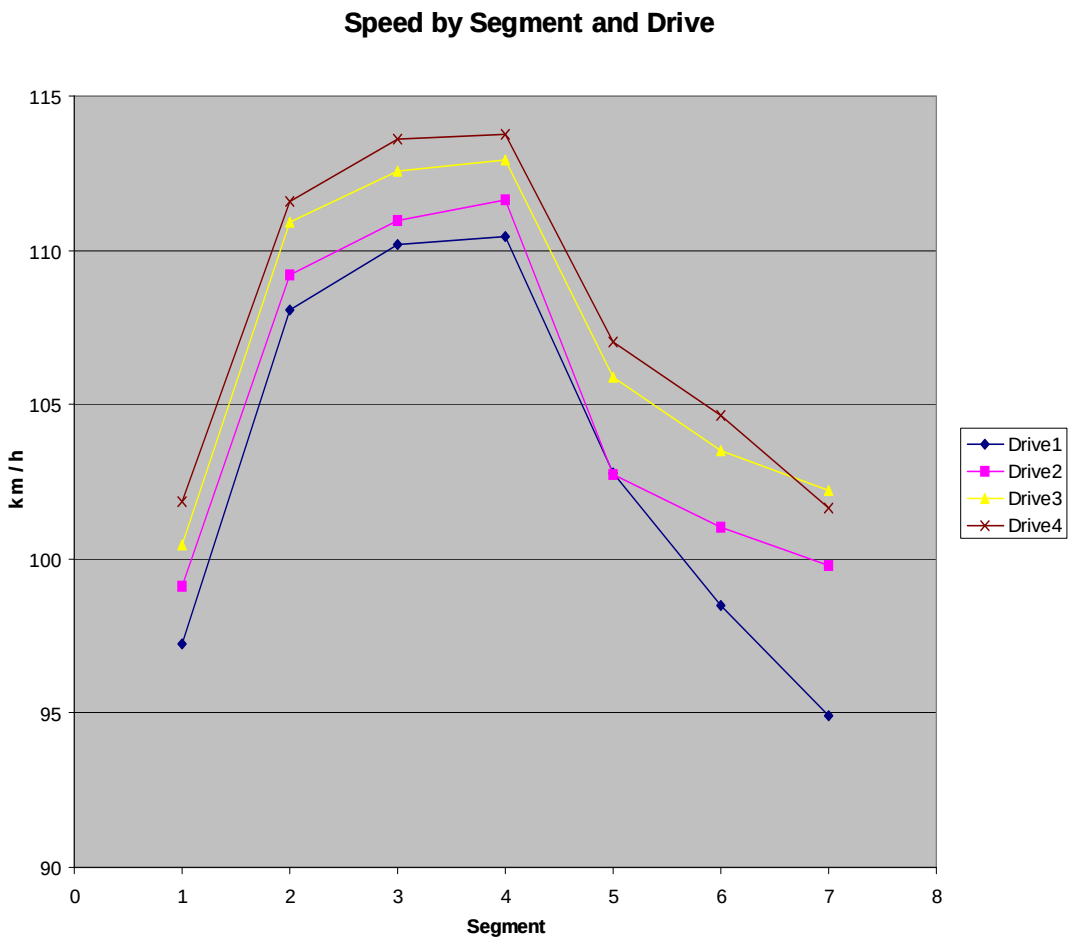

Figure 3.3: Average speed in the seven segments of the test route for the four drives

3.2.2.2. Effect of Route Segment—In the current study the segments were of unequal length and had varying speed limits. As might be expected, Figure 3.3 shows that for all four drives there were changes in speed from segment to segment that essentially mirror the changes in the speed limits in the segments.

3.2.3. Stopping Behavior

We examined the effect of time of day on both the stopping behavior of the drivers on the approach to the stop-controlled intersections and the distance from the intersections at which the drivers began to slow down (i.e., took their foot off the accelerator).

3.2.3.1. Stopping Behavior on the Approach to Stop-Controlled Intersections—To determine the effects of time of day on stopping behavior, we analyzed the speed of the CMV drivers on the approach to the stop-controlled intersections. The first intersection, which was 2,886 meters (1.79 miles) from an intersection controlled by traffic lights, was controlled with stop signs and rumble strips—the rumble strips were 218 and 118 meters (715 feet and 387 feet) from the intersection. The second intersection, which was 7,061 meters (4.39 miles) from the first

intersection, was controlled only with stop signs. To examine stopping behavior, we divided the final 418 meters (1,371 ft) of the approach to the intersections into fifteen segments (the segmentation scheme is shown in Table 2.3). The mean speed in each of the segments was determined for both intersections. The summary of the ANOVA was used to analyze these data is presented in Table 3.3.

Table 3.3: Summary of ANOVA conducted on mean speeds on the approach to stop-controlled intersections

Source of Variance	Degrees of Freedom	Mean Squares	Variance Estimate	F-Value	*p*-Value
Subjects	19	217988.19	11473.06		
Intersections	1	6289.67	6289.67	16.376	**0.0007**
Error Term I (Intersections X Subjects)	19	7297.70	384.09		
Time of Day	3	1484.57	494.86	0.652	0.5848
Error Term II (Time of Day X Subjects)	57	43239.58	758.59		
Segments	14	1525413.28	108958.10	466.932	**<0.0001**
Error Term III (Approach Segments X Subjects)	266	62070.85	233.35		
Intersections X Time of Day	3	552.25	184.08	0.918	0.4379
Error Term IV (Intersections X Time of Day X Subjects)	57	11425.89	200.45		
Intersections X Approach Segments	14	12062.24	861.59	15.344	**<0.0001**
Error Term V (Intersections X Segments X Subjects)	266	14946.28	56.19		
Time of Day X Approach Segments	42	3313.06	78.88	1.892	**0.0007**
Error Term VI (Time of Day X Approach Segments X Subjects)	798	33266.81	41.69		
Intersections X Time of Day X Approach Segments)	42	1585.03	37.74	1.198	0.1850
Error Term VII (Intersections X Time of Day X Approach Segments X Subjects)	798	25130.30	31.49		

As Table 3.3 shows there were two statistically significant main effects. First, inevitably, as the drivers approached the intersections, their mean speed progressively decreased. And, as expected, the rumble strips affected mean speed—their presence caused drivers to reduce speed to a greater extent earlier in the approach.

Table 3.3 also shows that there were two statistically significant interactions. There was an interaction is between the presence/absence of rumble strips and segments. The second interaction is of particular interest because it indicates that the time of day had an effect on the speed of the drivers as they approached the intersections. This interaction is illustrated in Figure 3.4.

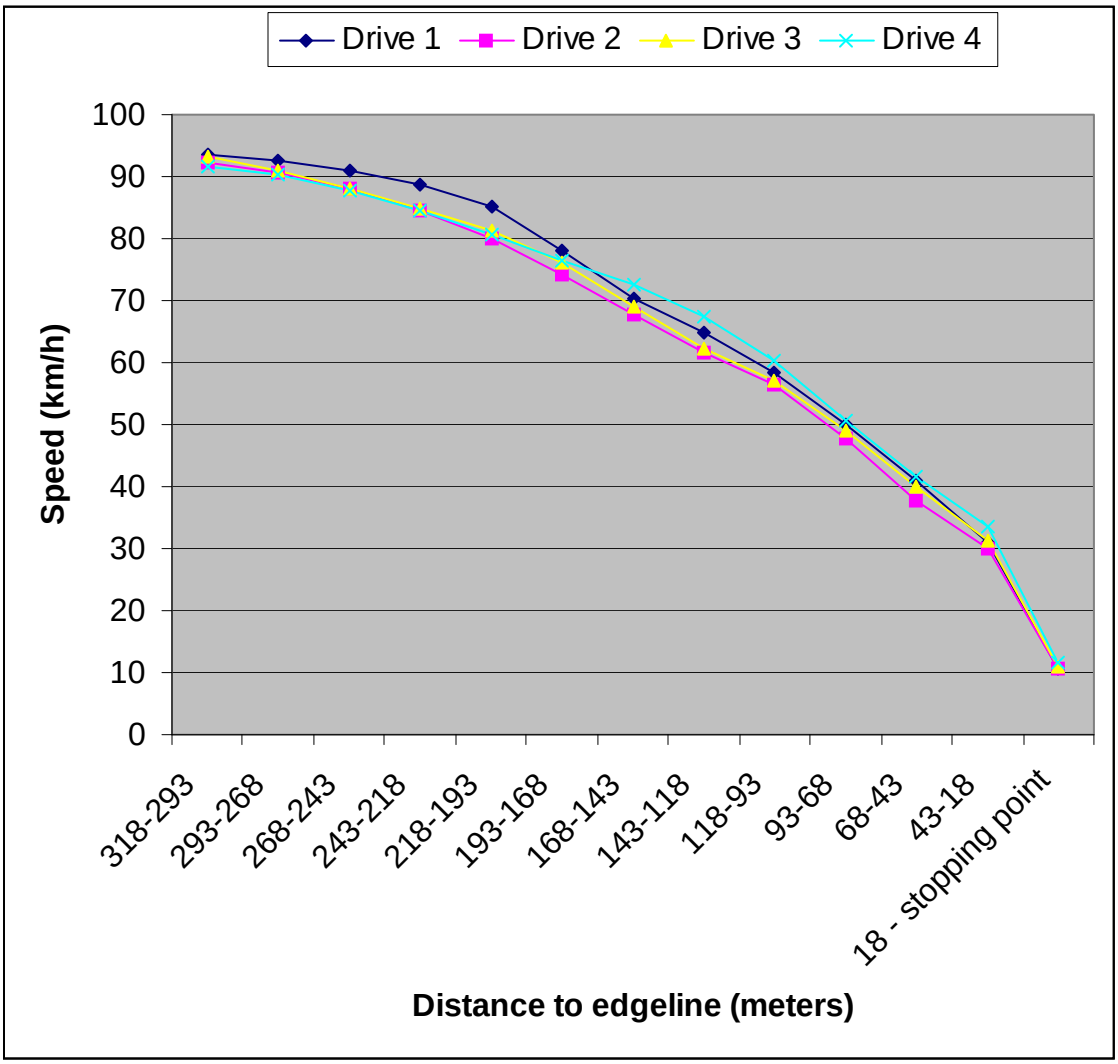

Figure 3.4: The difference in mean speed on the approach to the intersections for the four drives

In addition to the main effect—that as drivers approached the intersections, mean speed progressively decreased—Figure 3.4 shows the interaction between time of day and segments. On the first drive of the day, participants drove faster earlier on the approach—when they were between 268 meters (879 ft) and 168 meters (551 ft) from the intersections—than they did on the subsequent three drives. The difference between speed in the first drive and the subsequent three drives suggests that the participants adjusted their behavior when they became more familiar with the test route. Most interestingly, there was no indication that the stopping behavior of the participants was affected by sleep deprivation.

3.2.3.2. Beginning of the Slow Down—We also determined the distance from the intersections at which each driver began to slow down (i.e., took his/her foot off the accelerator) on the four drives. An ANOVA was conducted on these data. The summary of this ANOVA is presented in Table 3.4.

Table 3.4: Summary of ANOVA conducted on distance from intersections at which drivers began to slow down

Source of Variance	Degrees of Freedom	Mean Squares	Variance Estimate	F-Value	*p*-Value
Subjects	19	1550016.71	81579.83		
Rumble Strips	1	136326.49	136326.49	7.553	**0.0128**
Error Term I (Rumble Strips X Subjects)	19	342940.07	18049.48		
Time of Day	3	124950.59	41650.20	3.582	**0.0192**
Error Term II (Time of Day x Subjects)	57	662781.11	11627.74		
Rumble Strips X Time of Day	3	43858.10	14619.67	1.837	0.1507
Error Term III (Rumble Strips X Time of Day X Subjects)	57	453609.84	7958.07		

Table 3.4 shows that there was a statistically significant difference in the distance from the first and second intersections at which the drivers began to slow down—they began to slow down when they were further from the intersection which had rumble strips.

The second statistically significant effect shown in Table 3.4 is of more interest—because it relates to the effects of time of day. It is explored further in Table 3.5.

Table 3.5: Mean distance in meters (and feet) at which drivers began to slow down as a function of time of day

Time of Day	Distance
9:00 am (1st Drive)	360.52 meters (1,182.81 ft)
3:00 pm (2nd Drive)	375.96 meters (1,233.46 ft)
9:00 pm (3rd Drive)	373.68 meters (1,225.99 ft)
3:00 am (4th Drive)	433.14 meters (1,421.06 ft)

Table 3.5 shows that in their first drive at 9:00 am in the morning the drivers began to slow down closer to the intersections, than they did in the three subsequent drives. The increase in distance from 360.52 meters (1,182.81 ft) for the 9:00 am drive and 433.14 meters (1,421.06 ft) for the final 3:00 am drive suggests there was a learning effect as the drivers became more familiar with the test route—rather than a decrement in performance related to sleep deprivation.

3.3. Other Performance Data

3.3.1. Visual Performance

Three measures were collected with the pupillometer—(1) the time in milliseconds from the beginning of the flash to the moment that the pupil started to constrict; (2) the time in milliseconds from the beginning of the flash to the moment that the pupil was fully constricted; and (3) the reduction in pupil size. Each participant was tested with the pupillometer immediately before and immediately after each drive.

We analyzed the pupillometer data by conducting six ANOVAs—with three ANOVAs, we compared the scores obtained *before* the participants began each drive, while with the other three ANOVAs, we compared the scores obtained *after* the participants completed the drives. Only one of the measures, the reduction in pupil size *after* the four drives were completed, was statistically significant (at the p=0.0122 level)—after the fourth drive, on average, there was significantly less reduction in pupil size for the participants. There were no statistically significant differences in the three measures obtained with the pupillometer before the drives began—i.e., there was no evidence to indicate that these measures could be used to predict sleep deprivation, fatigue or the increase in steering instability that occurred for the CMV drivers in the final 3:00 am drive. The results of the current experiment suggest that pupillometer data is of little relevance as a predictor of fatigue for CMV operators in the real world.

We also collected visual performance data using the Snellen-equivalent acuity and contrast sensitivity tests. These tests were conducted four times throughout the experimental session—after the first drive and before the second, third and fourth drives. ANOVAs were conducted on both sets of data—there were no statistically significant differences in either the Snellen-equivalent acuity data or contrast sensitivity scores. Neither measure was affected by the time of day at which it was collected.

3.3.2. Reaction Time

Reaction time data were obtained using the PVT and the code substitution test. Like the Snellen-equivalent acuity and contrast sensitivity tests, the two reaction time tests were administered four times throughout the day—after the first drive and before the second, third and fourth drives.

3.3.3.1. PVT—The average reaction time of the fastest ten percent of the responses with the PVT was determined for each participant. An ANOVA of these data indicated that time of day did have a statistically significant effect ($p=0.008$). The average reaction time of the fastest ten percent of responses was significantly faster when the PVT was administered at in the evening before the third drive—this suggests that there may have been a practice effect. However, since there were no statistically significant differences in this measure on the other three occasions that it was administered, the PVT did not predict fatigue or the driving performance of the CMV operators in this study.

3.3.3.2. Code Substitution Test—The number of correct responses for each participant in each ten-minute testing period with the code substitution test was determined. An ANOVA conducted on these data indicated that there was statistically significant time of day effect ($p< 0.01$). However, since the performance of the participants improved from the first test conducted after the first drive of the day to the fourth test conducted at before the final drive, at 3:00 am, this effect appears to have been a practice effect.

Chapter 4: Summary and Conclusion

4.1. Fatigue

Driver fatigue is an important causal factor in many highway crashes. It is of particular concern in the trucking industry where many CMV operators undertake long haul drives with only limited amounts of sleep. It has been estimated that 1,200 deaths and 76,000 injuries annually may be attributed to fatigue-related factors at a cost of $12.4 billion. Previous studies suggest that fatigue can affect steering performance and speed control. In real world driving studies and in driving simulator studies, steering performance has been found to gradually worsen with time. Also there is some evidence that fatigue affects driving speed, although the evidence is somewhat contradictory—drivers were found to increase their speed the longer they drove in a simulation study, while, in contrast, a survey of military truck drivers suggested that when drivers are fatigued, some drive at slower speeds, and others have difficulty estimating their speed correctly.

Fatigue is a subjective state related to sleep deprivation, and in the study reported here, the relationship between sleep deprivation and the driving performance of CMV operators was explored. Unlike most previous studies of sleep deprivation and driving performance, in this study we controlled what the participants did from their first drive (at 9:00 am) till the fourth drive (at 3:00 am). We determined the driving performance of each participant in a single experimental session. Our objectives were to determine: (1) the effect of sleep deprivation on the driving performance of CMV drivers; and (2) the effect of sleep deprivation on the visual performance and reaction times of CMV drivers.

4.2. Method

Twenty CMV operators, recruited with the help of the Minnesota Trucking Association, participated in the study. During the experimental session, the participants were continuously kept awake. We obtained driving performance, visual performance and reaction time data from each participant at various times during the experimental session. The participants drove in an advanced driving simulator for approximately one hour four times during the session. Driving performance data were obtained in the morning, the afternoon, the evening and at night. Also, three visual performance tests and two reaction time tests were administered during the experimental session. Then, at the end of the session, each participant was driven to the University of Minnesota's General Clinical Research Center, where he or she was able to sleep for eight hours

The participants drove in a fixed-base advanced driving simulator with a 210-degree forward field-of-view. Rear-view imagery was provided in two ways—(1) by a screen that the participants could see through the vehicle's rear-view mirror, and (2) via two LCD panels were installed in place of the simulator vehicle's side-view mirrors. The virtual position of the simulator vehicle, relative to the scenario that the participant was driving, was recorded at a rate

of 20 Hz throughout each experiment drive. From this record, it was possible to determine the participant's steering performance and the speed at which he or she was driving the vehicle.

The test route had three sections—a 46-mile (74-km) section of four-lane divided highway, a 12.5-miles (20-km) section of two-lane road, and finally a 1-mile (1.6-km) section of four-lane divided highway. The route was designed with the various features at different distances and with changes in the speed limits in order to make the driving experience more like real-word driving and to make it less easy for the participants to predict when they would encounter the various features on the route. During the route there were five overpasses, with exit and entry ramps, three intersections controlled with traffic lights, and two stop-sign controlled intersections, the first of which had rumble strips as well as stop signs. The speed limit was either 55 mph or 65 mph throughout the route.

4.3. Results

4.3.1. Steering Performance

The results indicated that there was a considerable increase in steering instability when the morning drive (at 9:00 am) was compared to the nighttime drive (which began 18 hours later at 3:00 am). Also, this result—obtained in a driving simulator with participants who were tested in a single experimental session—is consistent with the data reported by Åkerstad *et al*. In the Åkerstad *et al*. study, there was as increase in the magnitude of lateral deviations of shift workers after they had worked the night shift as compared to their driving performance after they had a normal night's sleep.

Also, the increase in steering instability value during the afternoon drive (at 3:00 pm) as compared to values obtained in the morning (at 9:00 am) and evening (at 9:00 pm) suggests that there was a diurnal or circadian rhythm effect.

4.3.2. Speed

The average driving speed of the participants was lower during the first drive (at 9:00 am) than in the third and fourth drives (at 9:00 pm and 3:00 am). There are two possible explanations for this result. The participants may have driven faster because they were fatigued—a result consistent with the findings of Hargutt, Hoffmann, Volrath, and Kruger (2000). Alternatively, they may have driven faster as they became more familiar with the test route. Unfortunately, it is not possible to decide between these two possibilities.

4.3.3. Stopping Behavior

We examined the effect of time of day on the stopping behavior of the drivers as they approached the two stop-controlled intersections. Inevitably, as the participants approached the intersections, their mean speed progressively decreased. In addition, for the first drive of the day (at 9:00 am), the participants drove faster earlier on the approach than they did on the subsequent three drives (at 3:00 pm, 9:00 pm, and 3:00 am). This suggests that they adjusted their behavior as they became more familiar with the test route. However, there was no indication that the stopping behavior of the participants was affected by sleep deprivation.

We also determined the distance from the intersections at which each participant began to slow down (i.e., took his/her foot off the accelerator). We found that with the first drive (at 9:00 am) the participants began to slow down when they were closer to the intersection, than they did in the three subsequent drives. The increase in the distance from the intersections between the first drive (at 9:00 am), and the final drive (at 3:00 am) at which the participants began to slow down suggests that there was a learning effect as they became more familiar with the test route—rather than a performance decrement related to sleep deprivation.

4.3.4. Other Performance Data

In addition to the driving performance data, we obtained visual performance data at various times throughout the experimental session. With the pupillometer, we found that only one of three measures—the reduction in pupil size *after* the completion of the drives—was statistically significant: We found, after the fourth drive (at 3:00 am), that on average, there was less reduction in the pupil size of the participants. However, there were no significant differences for the measures obtained with the pupillometer *before* the drives—so we did not find evidence to suggest that the pupillometer could be used to predict sleep deprivation, fatigue or the increase in steering instability that occurred for the CMV drivers in the fourth drive (at 3:00 am). In addition, the data obtained with the Snellen-equivalent acuity and contrast sensitivity tests did not show any affect of the time of day.

We also obtained reaction time data throughout the experimental session. The results obtained with the two reaction time tests did not show decrements related to the time of day. To the contrary, the data obtained with both the PVT and the code substitution test, suggested that performance improved and there may have been practice effects.

4.4. Conclusion

The main result of the study, investigating the driving performance of twenty CMV operators over a twenty-hour period in which they were continuously kept awake, was that their steering performance deteriorated during the experimental session. There was considerable increase in steering instability that occurred between the morning drive, at 9:00 a.m., and the nighttime drive, which began at 3:00 a.m. And this increases in steering instability seems likely to have been produced by sleep deprivation.

There are always issues with the validity of simulator studies. It would be difficult to replicate the current study in the real world. It would be too dangerous to conduct a similar study using a 59.5-mile (95.8-km) route on real world highways while investigating the driving performance of sleep-deprived drivers. However, this study, which was conducted under laboratory conditions—but allowed the participants to ingest caffeine and use tobacco as they would in real-world conditions—suggests that the steering performance of professional CMV drivers is likely to be impaired if they are awake from 8:00 or 9:00 am morning until they attempt to drive eighteen or more hours later at 2:00 or 3:00 am in the middle of the night.

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Appendix A:
Screening Questions

The following set of questions was used to screen all those who were interested in the study.

1. Personal Details
Name_____
Telephone number_____

2. Job Related
When do you usually start work?_____
When do you usually finish working for the day?_____
Do you work irregular shifts? _____
Are you a third shift worker (11:00 PM to 7:00 AM)?_____

3. Driving experience
Do you have a current driving license? _____
How long have you had a driving license? _____
Are you between the ages of 25 and 60? _____

4. Eyesight
Do you have glasses or contact lenses? _____
If you do have glasses or contact lenses, when did you last have your eyes tested?_____
If you do not have glasses or contact lenses, has a doctor or other health professional told you that you should have your eyes tested? _____

5. (For female subject) Pregnancy
Are you pregnant?_____
When was your last menstrual period?_____
[Screener will inform subject that] If selected for this study, you will be required to take a Pregnancy Test at the Preliminary Screening Visit and at the beginning of the Main Study. And only if the pregnancy tests are negative, will you be able continue on in the Main Study. If the Pregnancy Test is positive, you will *not* be allowed to continue on in the Main Study_____
Do you have a young child who you are still breast feeding?_____

6. Headaches and Motion Sickness

Do you get migraines or severe tension headaches?_____
Do you have motion sickness in automobiles?_____
Do you have motion sickness in airplanes?_____
Do you get sick on any amusement park rides?_____
Do you feel queasy at IMAX presentations?_____

7. Medical

Do you have a sleep disorder?—e.g., such as sleep apnea, insomnia or narcolepsy._____
When was your last complete physical examination at the doctor's?_____
In that visit, did you have blood tests? _____
In that visit, did you have a urine test?_____
Were any diagnostic tests ordered?_____
If you did what were the results of those tests?_____
Did the doctor prescribe any medicines as a result of that visit?_____
Did you get a prescription after the physical?_____
When did you last see your doctor?_____
Did you get a prescription on that visit?_____
What prescription medications are you taking at the moment?_____
How many times a day do you take prescription medications?_____
At what time(s) of day do you take prescription medications?_____
What over the counter medicines are you taking at the moment?_____
Do you take anything for headaches?_____
Do you take anything for allergies?_____
Do you take any vitamins?_____
Do you take any herbal supplements?_____

8. Alcohol Consumption

How often do you drink alcohol?

—Almost every day.
—Five or six days a week.
—Three or four days a week.
—Once or twice a week.
—Once or twice a month.
—Once or twice a year.

How many days did you drink last week?

—0.
—1.
—2.
—3.
—4.
—5.
—6.
—7.

When you drink, how many drinks per day do you have?

—0.
—1.
—2.
—3.
—4.
—5.
—6.
—7.
—8 or more.

If you are selected for this experiment, would you be willing to consume alcohol up to 0.04 before your last drive in the driving Simulator?_____

Also, if you are selected for this experiment, would you be willing to <u>not</u> drink any alcohol the day before the experiment?_____

<u>9. Caffeine Consumption</u>

How many cups of coffee do you drink a day_____

How many caffeinated beverages like Coke, Pepsi, Mountain Dew, Jolt, Surge, etc. do you drink a day?_____

<u>10. Tobacco Consumption</u>

Currently, do you use any form of tobacco._____

Have you ever used any form of tobacco?_____

If yes, when did you last use it?_____

<u>11. Length of Main Study</u>

The Main Study will last for as long as 30 hours.

Are you willing to stay for as long as 30 hours?_____

After your last drive in the simulator, for safety reasons, you must stay at the Sleep Facility for approximately ten hours._____

Are you willing to stay in the Sleep Facility for as long as eleven hours?_____