PB2001-103189

U.S. Department
of Transportation
National Highway Traffic Safety Administration

People Saving People
www.nhtsa.dot.gov

DOT HS 809 202

March 2000

Biobehavioral Responses to Drowsy Driving Alarms and Alerting Stimuli

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT HS 809 202		

4. Title and Subtitle	5. Report Date
BIOBEHAVIORAL RESPONSES TO DROWSY ALARM AND ALERTING	March 2000
	6. Performing Organizational Code
7. Author(s) M. Mallis, Ph.D., G. Maislin, M.A., N. Konowal, V. Bryne, M.S., D. Bierman, R. Davis, M.S.E., R. Grace, Ph.D., D. Dinges, Ph.D.	8. Performing Organization Report No.
9. Performing Organization Name and Address National Highway Traffic Safety Administration	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. DTNH22-93-D-07007
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration 400 Seventh Street, S.W. Washington, DC 20590	13. Type of Report and Period Covered NHTSA Contractor Report
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This final report examines the pattern of biobehavioral responses to drowsy driving alarms and alerting stimuli. Following a standard overnight express run, commercial heavy-vehicle drivers completed an additional 4 hour run in a heavy-vehicle driving simulator. Previous research had validated the percentage of eyelid closure over the pupil over time (PERCLOS) as a generally useful and reliable biobehavioral index of lapses in visual attention (NHTSA Final Report, DOT HS 808 762). Results of the present study showed that the drivers anticipated the onset of the audible drowsiness alarm, from moment to moment, and initiated normal self-alerting behavior until the visual drowsiness indicator decreased. Driver response profiles revealed a pattern of increased general activation of alerting behavior when alarms were anticipated, as opposed to a pattern of predictable unit decreases in alertness following each alarm or alerting stimuli. Lane-keeping performance also improved in the feedback conditions during the return leg of the simulated run.

17. Key Words	18. Distribution Statement
	Document is available to the public through the National Technical information Service, Springfield, VA 22162

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-72) Per FORM PRO/Delrina 04/04/94 Reproduction of completed page authorized

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

A controlled experiment was undertaken with n = 16 CDL holders driving a high-fidelity truck simulator (TruckSim®) to establish the effects of informational feedback about drowsiness while driving on: (1) driver alertness-drowsiness; (2) driving performance; and (3) driver-initiated behaviors. The drowsiness feedback system tested was developed at Carnegie Mellon Research Institute (CMRI) and was comprised of an infrared, retinal reflectance, on-line PERCLOS monitor that provided minute-to-minute feedback to drivers regarding their alertness-drowsiness, via a visual gauge (green-amber-red light sequence) which could trigger a tonal alarm and either a voice warning alert or a peppermint scent coupled with a buzzer alert, if drowsiness was sustained or reached high levels. Subjects served as their own controls, driving one simulated 4-hr night drive without PERCLOS feedback (control condition), and one simulated 4-hr night drive with PERCLOS feedback. Order of drive and type of warning alert within drives were counterbalanced across subjects. To ensure a dynamic range of alertness-drowsiness, drivers completed the two nighttime simulated drives between the hours of 5:00 a.m. and 10:00 a.m., after completing a normal night drive for their company. Drivers felt the TruckSim® simulator and nighttime driving scenario were realistic and they drove in a professional manner, avoiding collisions and completing the drives in the required times.

Although there was significant between-subject variability in drowsiness and consequently in the number of PERCLOS-based alarms and warning alerts, PERCLOS feedback tended to have five consistent effects on key classes of outcome variables.

(1) Feedback reduced PERCLOS measures of drowsiness (both on average and as a function

of time on task [slope across the drive]).

(2) PERCLOS feedback improved driving performance by reducing variability in lane tracking and steering.

(3) PERCLOS feedback was associated with increases in drivers' physical movements while driving (e.g., more face, shoulder and neck rubbing; more postural changes; and more total body movements). However, analyses of the timing of events within the PERCLOS feedback condition revealed no evidence that drivers' behaviors tended to cluster concomitantly with PERCLOS feedback signals, suggesting that drivers increased head rubbing and postural changes to enhance alertness but not specifically or exclusively in response to PERCLOS indications of drowsiness (see Appendix for these analyses). Thus, the presence of PERCLOS feedback appeared to have a generalized effect on drivers by prompting them to initiate more compensatory behaviors.

(4) PERCLOS feedback decreased drivers' ratings of sleepiness after the drive, but this effect was very transient.

(5) PERCLOS feedback was perceived by the majority of drivers as having improved their alertness levels.

The first three effects (on drowsiness indices, driving performance, and in-cab behaviors) were somewhat more likely to occur during the inbound (return) drive, which consistently involved greater drowsiness than the outbound drive. The consistency across these three domains suggests that drivers reduced their drowsiness and driving variability during the PERCLOS feedback condition by becoming more physically active in the cab. However detailed analyses of the relationship between

PERCLOS values and drivers' behaviors did not reveal a tight temporal contingency between PERCLOS feedback and drivers' behaviors (se Appendix). A number of drivers also reported qualitatively after the feedback drive that PERCLOS feedback prompted them to "concentrate" more on the driving task and on staying alert. This appeared to be the case for drivers who experienced a greater level of drowsiness during drives, which is precisely the subset of drivers for which a drowsy-driving detection and warning system should be optimized.

While drivers engaged in more activity while driving to enhance their alertness when PERCLOS feedback was present, they did not stop driving and take rest breaks when PERCLOS feedback indicated high levels of drowsiness (naps and caffeine were not permitted in the study). Future studies will need to determine whether an automated PERCLOS feedback system used by over-the-road truckers would prompt drivers to engage in napping and related countermeasures documented to reduce drowsiness for much longer periods of time than transient postural changes while driving. The consistency of PERCLOS feedback effects across drowsiness indices, driving performance metrics, behavioral variables, and drivers' perceptions of benefit, suggests that an automated PERCLOS drowsy-driving system should be transitioned to field studies (over the road) to answer a number of questions regarding its effectiveness and proper use.

ACKNOWLEDGMENTS

The research and substantive evaluation upon which this article was based were supported primarily by contract DTNH22-93-D-07007 from the U.S. Department of Transportation, which included support from the Federal Highway Administration--Office of Motor Carriers and support from the National Highway Traffic Safety Administration. Additional support for the projects was provided in part by the Institute for Experimental Psychiatry. We thank the volunteer subjects for contributing their time and best efforts in the conduct of these experiments. We appreciate the excellent cooperation provided at many levels by Pitt-Ohio Express, Inc. We acknowledge the following individuals for their assistance in performing this research: Barbara R. Barras, David Gricourt, Robert Hachadoorian, Jeff Hibner, Jim Jarrett, Jean-Michel LeGrand, Joe Nunez, Emily Carota Orne, Cindy Peters, Nicholas Price, Dr. James Staszewski, John Tabacchi.

INTRODUCTION

Recent technological initiatives in miniaturized monitoring of biobehavioral variables have accelerated the development of on-line, human-centered, objective monitoring technologies for tracking driver alertness-drowsiness (ATAF/FHWA/NHTSA, 1996; Dinges & Mallis, 1998). In a laboratory-based, independent validation study, we experimentally tested the scientific validity of six alertness-drowsiness on-line technologies to predict a dynamic range of performance lapses (Dinges et al., 1998). This project established that only one of the six monitoring approaches was highly accurate in detection of drowsiness-induced performance lapses (Dinges et al., 1998; Mallis et al., 1998). The highly accurate technique, which was developed and initially validated by Wierwille and colleagues (1994), is called PERCLOS. Its measurement in our validation study involved video-based human-scored measurement of the proportion of time subjects had slow eye closures during performance across a 42-hr period of wakefulness. Because PERCLOS proved to be accurate in predicting vigilance performance lapses across a wide range of alertness-drowsiness levels (i.e., high within-subjects accuracy), and in both lower and higher lapsers (i.e., high between-subjects accuracy), we concluded that it had the highest potential to form the basis of a practical on-line drowsy-driving detection system (Dinges et al., 1998).

Subsequent to this result, investigators at Carnegie Mellon Research Institute developed an objective PERCLOS monitor using infrared retinal reflectance. This device formed the basis of the current study, which sought to determine how truck drivers equipped with feedback from an objective PERCLOS monitor would react to driving with the PERCLOS feedback during simulated nighttime drives. PERCLOS feedback was provided in the form of continuous information regarding alertness-drowsiness, as well as audible warning alarms and alerts if drowsiness was severe or sustained. Using drivers as their own controls, the study focused on determining the effects of PERCLOS feedback (in the form of a visual gauge plus an audible alarm and alerts) on three classes of outcome variables: (1) driver drowsiness (as assessed by PERCLOS); (2) driver behavior (e.g., pulling off to take breaks, behavioral countermeasures); and (3) driving performance (e.g., lane deviations, collisions). The study was conducted in truck drivers operating a full fidelity truck simulator during a 4-hr simulated night drive, under time pressure, to enhance the ecological validity of the findings.

METHODS

STUDY DESIGN

The study design was fully within-subjects. Drivers served as their controls by having them complete two realistic nighttime simulated driving scenarios in four counterbalanced orders. Subjects were compared when driving under two different conditions: (1) a simulated night drive scenario under time pressure with PERCLOS feedback via a visual gauge, auditory alarms and alerting stimuli (i.e., feedback condition), vs. (2) a simulated night drive scenario under time pressure without PERCLOS feedback (i.e., control condition). Half of the subjects underwent the control condition first and the feedback condition second, and within each of these two orders, half received one sequence of alerts, and the half received the other sequence.

Table 1 displays the orders of conditions to which subjects were randomly assigned. For the PERCLOS drowsiness feedback condition, all subjects received informational feedback

Table 1. Orders of conditions to which subjects were randomly assigned.

# of subjects	First nighttime drive		Second nighttime drive	
	outbound drive (leg 1)	***inbound drive (leg 2)***	***outbound drive (leg 1)***	***inbound drive (leg 2)***
n = 4	**control condition** (no PERCLOS feedback)	**control condition** (no PERCLOS feedback)	**PERCLOS feedback condition** visual gauge + auditory alarm + **voice** alert: *"Warning, you are very drowsy. Take corrective action."*	**PERCLOS feedback condition** visual gauge + auditory alarm + **olfactory** alert: *peppermint odor + buzzer sound*
n = 4	**PERCLOS feedback condition** visual gauge + auditory alarm + **voice** alert: *"Warning, you are very drowsy. Take corrective action."*	**PERCLOS feedback condition** visual gauge + auditory alarm + **olfactory** alert: *peppermint odor + buzzer sound*	**control condition** (no PERCLOS feedback)	**control condition** (no PERCLOS feedback)
n = 4	**control condition** (no PERCLOS feedback)	**control condition** (no PERCLOS feedback)	**PERCLOS feedback condition** visual gauge + auditory alarm + **olfactory** alert: *peppermint odor + buzzer sound*	**PERCLOS feedback condition** visual gauge + auditory alarm + **voice** alert: *"Warning, you are very drowsy. Take corrective action."*
n = 4	**PERCLOS feedback condition** visual gauge + auditory alarm + **olfactory** alert: *peppermint odor + buzzer sound*	**PERCLOS feedback condition** visual gauge + auditory alarm + **voice** alert: *"Warning, you are very drowsy. Take corrective action."*	**control condition** (no PERCLOS feedback)	**control condition** (no PERCLOS feedback)

about their alertness/drowsiness levels via a visual gauge of green-amber-red lights as well as a tonal warning when drowsiness levels exceeded specified thresholds (see "Alarm/alerting system" below). However, in the PERCLOS feedback condition, half of the drivers (n = 8) received a peppermint olfactory alerting stimulus paired with an auditory buzzer when drowsiness was detected during the first half of the drive (outbound drive), and a voice warning auditory alerting stimulus ("Warning, you are very drowsy. Take corrective action.") when drowsiness was detected during the second half of the drive (inbound drive). The other eight drivers received the voice warning auditory alerting stimulus when drowsiness was detected during the outbound drive, and an olfactory peppermint + buzzer alerting stimulus when drowsiness was detected during the return (inbound) simulator drive.

SUBJECTS

A total of 16 healthy, male, truck drivers (ages 28.8 – 62.3 yr., avg. 41.5 yr.) were studied in a truck driving simulator protocol after completing their normal night shift driving schedules. All subjects: (1) held a CDL; (2) were currently employed by a trucking company located in the Pittsburgh, Pennsylvania area, and; (3) showed no evidence of current drug use or of major medical or psychiatric illness as determined by interview. Fifteen subjects typically drove over the road, short-haul (6-8 hr), out and back in the same nighttime period (sometime between the hours of 7:00pm – 7:00am). One additional subject was a dispatcher who met all eligibility criteria, except that he did not typically drive over the road at night, but instead worked a non-driving shift between 11:00p.m. and 8:00a.m.. The 16 subjects were obtained from a cohort of n = 19 volunteers recruited for the study; n = 3 volunteers did not participate in the study due to varying circumstances (one was excluded due to experiencing motion sickness in the simulator during a screening session; one resigned from the company; and another had unexpected schedule/route changes resulting in a work schedule that was not consistent with protocol eligibility). Table 2 displays the characteristics and sleep times (for each experimental run) for the subjects who completed both control and feedback conditions of the experimental protocol.

PROCEDURES

All aspect of the experimental protocol, procedures and informed consent were approved prior to initiating any investigation with subjects, by the Committee on Studies Involving Human

Recruitment Procedures

All volunteers were recruited from the population of drivers who regularly worked the nightshift at Pitt-Ohio Express, Inc., a Pittsburgh, Pennsylvania based trucking company. Trained research staff scheduled organized, formal briefings about the nature of the study on four separate occasions, allowing for flexibility in volunteers' work schedules. Each session lasted approximately 1-hour and took place at Pitt-Ohio Express, Inc. It included a brief review of past studies performed with Pitt-Ohio Express, Inc., a detailed description of the experimental protocol, estimated timeline of study dates and an explanation of all eligibility criteria. During this time, subject compensation and incentives were also reviewed. Those individuals who remained interested after explanation of all experimental procedures scheduled telephone-screening sessions.

Simulator Screening Procedures

There were three purposes of the simulator screening session. (1) The main reason was to ensure that the subjects would not experience any symptoms of simulator sickness during the experimental protocol sessions. Research has indicated that some individuals can experience nausea when immersed in a simulator environment. Therefore, in order the prevent the potential cancellation of one or more experimental sessions due to the onset of simulator sickness,

Table 2. Characteristics of subjects studied.

ID	age (y)	weight (lbs.)	height (Inches)	gender	order of conditions to which subject was randomized	mean total sleep time (TST) 3 days prior to study (hr)	TST (hr) day before study
2001	49	230	5'11"	male	1st drive = control	5.8	6.0
					2nd drive = feedback	5.0	3.5
2002	45	210	5' 10'	male	1st drive = feedback	7.5	7.0
					2nd drive = control	6.7	7.0
2005	31	155	5'9"	male	1st drive = control	6.1	6.0
					2nd drive = feedback	6.6	7.0
3001	32	160	5'9"	male	1st drive = feedback	7.2	10.1
					2nd drive = control	5.9	8.2
3003	41	194	6'0"	male	1st drive = feedback	9.0	6.2
					2nd drive = control	7.6	7.1
3004	38	185	6'10"	male	1st drive = feedback	8.5	7.2
					2nd drive = control	7.6	6.7
3005	35	215	6'0"	male	1st drive = control	4.0*	8.0
					2nd drive = feedback	7.3	7.5
3006	54	210	6'1"	male	1st drive = control	7.4	8.1
					2nd drive = feedback	6.3	5.2
3007	62	185	6'2"	male	1st drive = control	8.2	8.6
					2nd drive = feedback	8.8	9.2
3008	36	190	6'1"	male	1st drive = feedback	#	8.0
					2nd drive = control	6.8	7.5
3009	39	160	5'5"	male	1st drive = feedback	6.9	6.2
					2nd drive = control	7.0	6.7
3010	28	190	5'10"	male	1st drive = control	7.7	7.0
					2nd drive = feedback	10.1	10.5
3011	38	168	5'8"	male	1st drive = feedback	5.7	4.5
					2nd drive = control	5.9	4.5
3012	56	180	5'11"	male	1st drive = control	8.3	#
					2nd drive = feedback	9.0	9.0
3013	42	175	5'10"	male	1st drive = control	8.5	5.0
					2nd drive = feedback	6.1	8.5
3014	31	455	6'4"	male	1st drive = feedback	10.8	13.5
					2nd drive = control	#	10.5

* TST 2 days prior to study
# Missing data

screening sessions were scheduled approximately 1-2 weeks prior to the start of data collection during the experimental drives. (2) In addition, the screening session allowed researchers to confirm that each subject had adequate retinal reflection necessary for proper eye tracking and slow eye closure measurements (PERCLOS) in the driving simulator. (3) Finally, the screening session served to familiarize subjects with driving the simulator. A typical session lasted approximately 1.5 hours and all subjects were monetarily compensated for their participation in the simulator screening. Transportation and light snacks were provided. These screening sessions typically occurred immediately following a subject's night run.

Pre-drive activities. Each screening session started with volunteers reviewing and signing an Institutional Review Board (IRB) approved informed consent form. During this time, subjects also completed and signed all necessary payment forms. After giving fully informed consent, subjects answered questions pertaining to their sleep habits, as well as some additional medical questions. Subjects also completed food preference forms that were used to determine the types of food and non-caffeinated beverages they preferred to have available during the experimental sessions. Each subject also completed a Pre-Drive Simulator Sickness Questionnaire (SSQ) checklist (Kennedy et al., 1993) immediately before being escorted to the truck simulator. This was done in order to establish a baseline as to how the subject was feeling before driving the motion-based simulator.

Simulated drive activities. A research staff member escorted each subject to the room that housed the simulator where the subject entered the cab. The subject entered the TruckSim® cab and familiarized himself with all cab instrumentation. Each driver then received a briefing on use of the TruckSim® simulator and exact details of the initial familiarization drive. Subjects were instructed that at any time they wished to stop the simulation to simply state, "they wished to stop." An intercom installed in the cab of the simulator allowed the researchers to hear subjects' requests and comments. After the researcher left the room housing the simulator, the screening run began. The subject drove the truck simulator for an uninterrupted 30-minute interval. The 30-minute interval was chosen based on work done with other simulator studies suggesting that simulator sickness could occur as late as 20 minute into operation of the motion-based simulator.

Post-drive activities. Immediately after driving the simulator for a 30 minute period, the subject completed a Post-Drive Simulator Sickness Questionnaire (SSQ) checklist. After completion of the SSQ, the researcher asked the subjects questions concerning the simulator's performance with respect to: lights, mirrors, transmission, traffic, brakes, steering, engine sounds, and immersion quality. The researchers also carefully documented overall experience and general comments of the subject after driving the motion based simulator for 30 minutes. Based on the comments of some of the subjects during the simulator familiarization drive, changes were made to the simulator-driving scenario to increase its fidelity. Subjects were then scheduled for the experimental protocol if they continued to express interest after completion of the screening drive.

Experimental Protocol

All subjects (n=16) participated in two simulated night drives that started approximately between 3:00 a.m. and 7:00 a.m. All subjects participated in the protocol and were studied one at a time (i.e. the subject drove the simulated night run alone with no one else in the TruckSim® cab). The total duration of a simulated night drive was approximately 4 hours and typically occurred after the subject had completed a standard out-and-back, short-haul overnight drive or a layover run. This ensured that subjects were performing after a minimum of 12 hours awake and near their circadian time for vulnerability to drowsiness. All subjects were given the subsequent 24 hours off after completing each experimental simulated nighttime drive (i.e., they were driven home after each experimental session; they were not permitted to work the next day; and they were compensated for their time off and participation in the experimental protocol). The simulated night drive scenario consisted of a simulated overnight, out-and-back drive using the new Carnegie Mellon Research Institute truck simulator, CMRI TruckSim®, which is a high-fidelity ISIM Mark II Mobile Driving Simulator (See Truck Simulator Section for a detailed description). Subjects had to drive a total of 200 miles to complete a 4-hr experimental drive. This 200-mile drive was divided into 100 miles during the first half of the drive (outbound) and 100 miles during the second half of the drive (inbound) portion. Subjects were permitted a total of 4 hours and 10 minutes to complete the 200-mile drive but had to reach a midpoint destination and final destination under time constraints as shown in Figure 1. However, subjects were given some flexibility in their time constraints (±10 minutes leeway in arrival at the midpoint destination and/or the return destination). They were also allowed up to 15 minutes to stop driving during either of the two legs, and still reach destination in within the allowable time constraints (assuming they drove the posted speed limit of 60 mph).

Pre-drive activities. Approximately 4 days prior to a scheduled experimental session, the

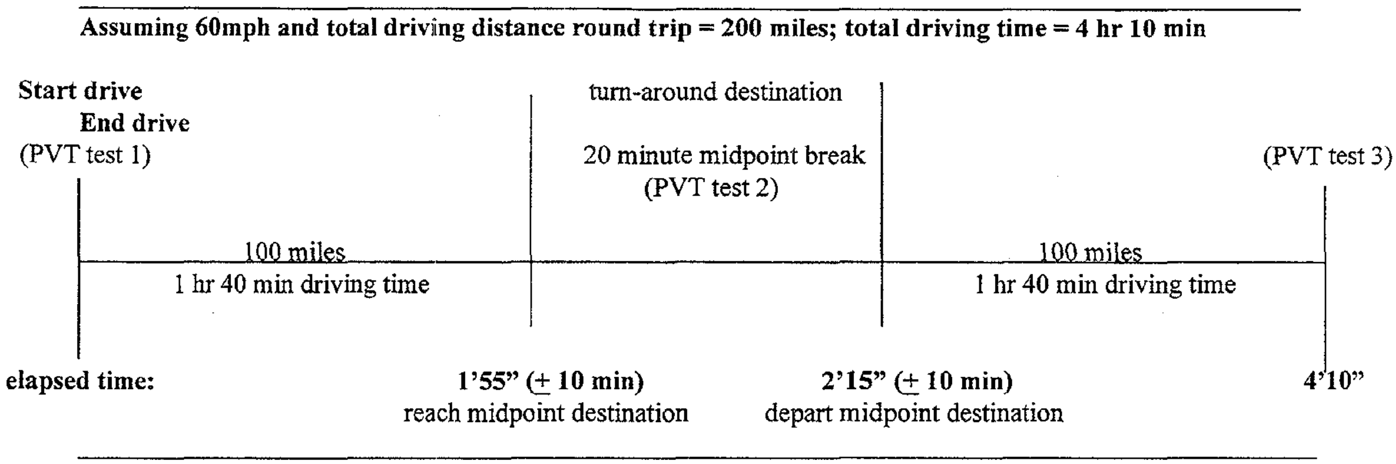

Figure 1. Experimental driving schedule

subject received an ambulatory wrist actigraphy monitor (Actigraph) and a personalized sleep diary to record sleep and wake times (see Table 2). Each subject also received detailed instructions for use of the Actigraph and completion of the sleep diary. A chartered car provided transportation from the subject's place of residence to Pitt-Ohio Express, Inc. either 2 nights prior to the experimental session (in the case of a 'layover' run) or 1 night prior to the study (in the case of an 'out and back' run). After reporting to work, the subject worked the scheduled shift ('layover' or 'out and back') and returned to the Pitt-Ohio Express, Inc.'s Pittsburgh terminal, typically between the hours of 2:30am – 6:30am the morning of the experimental session. Upon completion of the scheduled work shift, a charted car from Pitt-Ohio Express, Inc. to the simulator facility transported the subject, where a researcher met the subject.

Upon arrival at the simulator facility, the subject was escorted to a small conference room by a researcher. At this time the researcher instructed the subject to complete the final sheet of the sleep diary if it was not already completed prior to arrival at the simulator facility the subject also returned the sleep diary and Actigraph to the researcher. Prior to the simulated night drive run, the researcher conducted a standardized interview that consisted of questions pertaining to the duration between intermediate stops on the prior night's run; types of traffic and weather conditions encountered; the type and amount of the last caffeinated beverage consumed; and some questions pertaining to the duration and quality of the last major sleep period. After answering these questions, the subject selected food preferences from a menu, in case the subject desired to eat prior to the simulated run, during the midpoint break, after the simulated run or during any voluntary breaks

After completion of all questions in the pre-run interview and meal selections, the subject was administered the first 10-min Psychomotor Vigilance Test (PVT) trial, which is a sustained attention task validated to be sensitive to sleepiness (e.g., Dinges et al., 1997). As the subject began the PVT, the researcher stood nearby to ensure that the portable PVT unit was operating properly and that the subject was inputting the correct information. As soon as the reaction time portion of the test commenced, the researcher quietly left the room, closed the door for approximately 11 minutes to allow ample time for the subject to complete the PVT test free of distractions. After the subject completed the PVT test, the researcher re-entered the room, verified that the PVT data collection process was complete, and then administered to the subject the pre-run Simulator Sickness Questionnaire (SSQ). The researcher then described, in full detail, the specifications of the simulated night drive. The following was explained to the subject:

> *You will have 1hr and 55 min to travel 100 miles, and you should take all necessary steps that you would take during the course of a regular run to ensure that you arrive at the destination safely and on time (including, but not limited*

to, taking voluntary rest breaks and/or governing the truck's speed). If you arrive too early or too late, the time difference would either be added to or subtracted from your 20-minute midpoint break. Prior to beginning the simulated run, I will provide you with an informational mileage card (separate cards prior to the outbound portion of the drive and prior to the inbound portion of the drive) that will display the simulator odometer's starting mileage as well as your target mileage. The card also displays the expected start time and expected arrival times. It will be positioned in the cab directly above the backlit LCD clock, thereby providing you with all the information required to arrive at the 100-mile destination on time. We also ask that you treat the simulation like a real over-the-road run with regards to your driving habits; the only restrictions are that you are not permitted to eat food in the cab (except chewing gum, hard tack candy, etc), to drink caffeinated beverages of any kind, or to nap during any break period.

After the subject acknowledged the run specifications, the researcher explained the experimental condition to which the subject was randomly assigned for the first drive, either feedback or control. In the case of the feedback condition, the researcher explained the types of alerts (olfactory peppermint scent + buzzer, or auditory voice warning) the subject would receive and on what leg of his run he would receive the specified alerts. After answering all final questions the subject had concerning the exact details of the experimental protocol, the subject was offered a non-caffeinated beverage to drink during the simulated night run and was also given the opportunity to use the rest room. The subject was then escorted to the TruckSim® simulator by the researcher.

Upon entering the room where the simulator was located, the subject was instructed to enter into the simulator cab, make himself as comfortable as possible by adjusting the seat. The subject was also instructed to position himself in a position he felt he would remain throughout the duration of the drive. After the subject obtained a comfortable position, another researcher at the experimental console confirmed that the subject's face was in full view of the PERCLOS camera (via video monitors) and performed camera adjustments if necessary. Once the camera was properly positioned, the subject re-familiarized himself with the cab controls and again reoriented himself. Again, a confirmation of the PERCLOS camera position was made in case the re-familiarization process resulted in a position change of the subject.

In the case of a feedback session, the subject was also given a brief explanation of the visual gauge positioned directly in front of the subject (on the dash, below the top of the steering wheel arch), and was encouraged to test its operation by squinting momentarily and to watch the LED's light up (green-amber-red). Following this brief demonstration, the subject was reminded that if he needed to stop for any reason, that he should simply state it aloud. This also applied to the subject requesting to take voluntary breaks during the drives. The simulation could also be stopped immediately by the subject unbuckling the seatbelt. This was a safety precaution incorporated for any possible emergency procedures that would require immediate halting of the simulator.

Prior to beginning the simulated run, the researcher noted the current time on the cab's LCD clock, wrote it down (and the expected arrival time) on the appropriate location on the informational mileage card, and handed it to the subject to rest directly above the clock. This allowed for the subject to use their time and rest breaks accordingly to reach a destination point within a specified period of time. The researcher then left the simulator room, walked back to the experimenter's console, ensured that data collection was ready to begin, and then commenced the simulation. The subject was instructed over the intercom that he could begin the simulated drive whenever he was ready. This began the outbound portion of the simulated drive.

Outbound portion of the drive. During the course of the simulated drive, the researchers were located at an experimenter's console outside the simulator, from which they could record the performance of the simulator, the PERCLOS system, and the driver. Researchers also monitored the operation of the data collection program and the PERCLOS monitor, to verify that data were being stored properly and that the system was tracking the subject's eyes adequately. In addition, through each drive, one of the monitors kept constant video observation over the subject's behaviors inside the cab while driving, noting the times (minute by minute) and the specific nature of a wide range of physical behaviors (e.g. rubbing face, scratching head, head nodding, etc).

When the subject reached the 99th mile of the outbound portion of the drive, the researcher instructed (via the intercom) the subject to take the next exit, and to stop the truck at the stop sign at the end of the exit ramp (drivers also had an odometer that indicated the total miles covered and therefore the distance remaining). When the truck came to a complete stop, the researcher noted the elapsed time from the beginning of the run, and added any additional time above and beyond the 10-minute "grace period" to the total time for the midpoint break.

Midpoint break activities. Upon completion of the outbound portion of the simulated drive, the researcher entered the simulator room and escorted the subject back to the small conference room. After giving the subject an opportunity to use the restroom facilities, the subject was administered the mid-exposure SSQ to confirm that there was no onset of simulator sickness. Immediately following completion of the SSQ, the subject performed a second 10-min

PVT test. After the subject completed the PVT trial, the researcher confirmed that the data had been gathered properly. At this point, the subject spent the remainder of the midpoint break eating whatever food he requested, and reading (typically either something of his own, or something from a stack of recent local papers). At no time during either simulator drive condition were subjects permitted to take naps or ingest caffeinated food or beverages, since these two drowsiness countermeasures could have altered the experimental results. After the midpoint break period of approximately 20 minutes had elapsed, the subject was escorted back to the simulator, given a new mileage/time card, and told to begin the return (inbound) simulated drive whenever he was ready.

Inbound portion of the drive. As soon as the simulator commenced forward motion, the second leg of the run, or the inbound portion of the drive, was officially underway. Subjects were instructed that they had 1 hour and 55 minutes that allowed for 15 minutes of voluntary breaks to drive the second 100 miles and reach their home destination, just as each subject was allowed during the outbound portion of the drive. Subjects were also instructed to obey the posted speed limits of 65mph throughout the entire drive. The same protocol, experimental procedures and time constraints implemented in the outbound portion of the drive were also implemented in the inbound portion of the drive. This included monitoring the experimenter's console, confirming that all equipment was functioning adequately, ensuring the integrity of data collection and monitoring all behaviors of the subject during the drive on a minute-by-minute basis. Inbound drives typically occurred between 5 a.m. and 9 a.m., although the driving simulation remained a nighttime scenario for the entire duration of the drive.

Post-run activities. Upon completion of the inbound portion of the drive, the researcher escorted the subject back to the small conference room, and administered the post-run SSQ, followed by the third (and final) 10-min PVT trial. During the PVT test, the researcher verified the integrity of the data (both PERCLOS and driving data) from the entire run, and archived a copy of it. Following the PVT test, subjects were fully debriefed at the end of their participation in the simulated run, regarding their perceptions of, and reactions to, the study conditions, technologies and procedures. The experimenter administered a post-run interview, which consisted of questions pertaining to how the subject felt at the present time upon conclusion of the simulated night run, questions eliciting general feedback with respect to simulator fidelity; a subjective assessment of his PVT performance; and in the case of a subject in the feedback condition, asked questions pertaining to the various alerting stimuli received (i.e., peppermint scent + buzzer and voice warning). Following this, the subject was escorted outside by the researcher, where a car was waiting to drive him home. Subjects received the night of the experimental run off from their regularly-scheduled work shift to permit recovery sleep and mitigate any risks while driving their regularly scheduled shift that may have accrued as a result of the sleep deprivation to complete the protocol.

TruckSim® Simulator Description

The TruckSim®, developed by The Carnegie Mellon Driving Research Center (DRC) and ISIM Corporation, is a state-of-the-art driving simulator that has been targeted for use in human centered research (Grace et al., 1998). TruckSim® has been designed to provide a realistic driving experience with a balanced perceptual environment of realistic visual, motion/vibration and sound cues. For the current study, TruckSim® was configured as a Class 8 truck with a Freightliner FLD cab. The Freightliner FLD cab used on the simulator was equipped with a dedicated sound system plus sensor, and actuators associated with the driver controls and displays. TruckSim® also included an experimenter console where researchers were able to effectively implement the experimental design.

<u>TruckSim® design.</u> The TruckSim® design is based on the ISIM Mark II simulator. Figure 2 shows the simulator configuration. TruckSim's® visual system provided a forward field of view and two side mirror views. The forward field of view was implemented with three LCD projectors each providing 1200 x 1000-pixel resolution within each 60° of view. The side view mirrors were implemented in LCD displays. The visual database used in the current research consisted of a 21-mile highway loop. The motion system includes a 4-degree of freedom motion

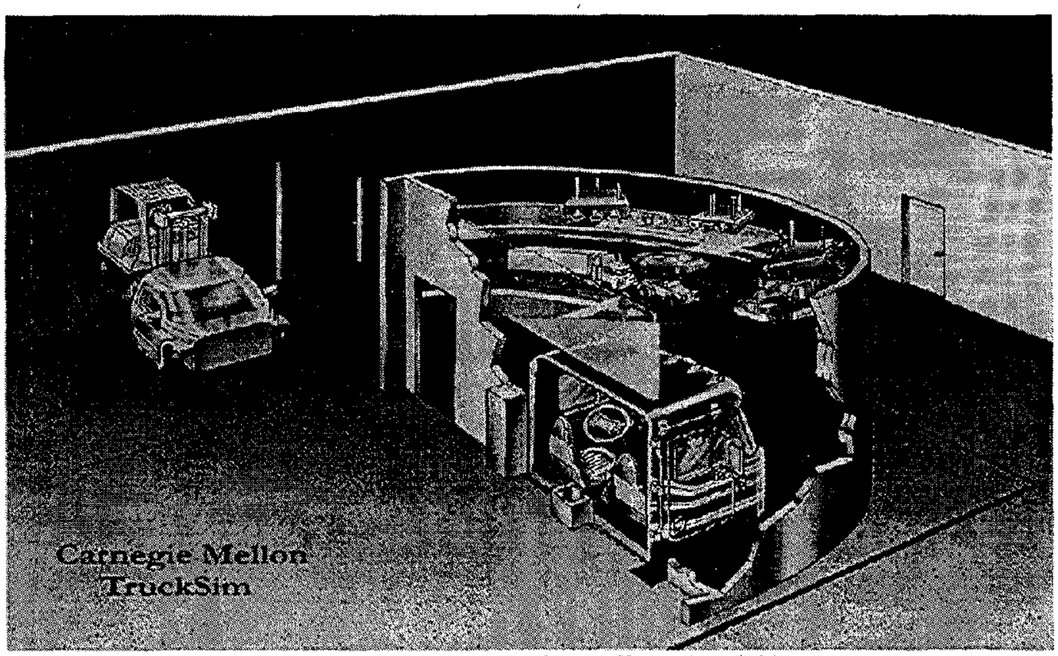

Figure 2. Carnegie Mellon TruckSim®

Table 3. TruckSim® simulator design.

Motion System • Motion platform degrees of freedom - 4 - roll, pitch, surge and heave • Roll angular amplitude and acceleration - ± 6 degrees, 1 G maximum acceleration • Pitch angular amplitude and acceleration - ± 6 degrees, 1 G maximum acceleration • Surge linear amplitude and acceleration - 0.1 meters, 0.5 G maximum acceleration • Heave linear amplitude and acceleration - 0.1 meters, 0.5 G maximum acceleration • Small amplitude bandwidth - 15 Hz • Maximum latency of motion system – 50 milliseconds • Motion simulation capabilities - road surface irregularities (i.e., potholes, rumble strips, uneven road surface), off road surfaces (i.e., curb, soft shoulder, driving off road surface), tactile response for multiple tire types	**Visual/Audio System** • Angular field of view - 180 degrees horizontal, 33 degrees vertical • Forward display channels - 3 channels, 1000 x 800 pixel resolution • Brightness of forward channel projectors - 300 lumens • Rear display channels type - 2 channels, 600 x 480 pixel resolution, flat panel • Minimum screen drawing rate - 30 Hz • Anti-aliasing - implemented in hardware • Projector position - inside of screens • Number of moving vehicles per channel - 100 • Number of sound channels – 4 • Sound simulation capabilities – multiple tire type sounds, velocity dependent wind noise, transmission grinding cue, additional sounds can be added
Traffic Control • Number of traffic objects - over 100 objects (vehicles, pedestrians, etc.) • Automated intelligent traffic control – control of traffic density, aggressiveness, circulatory and Swarm traffic • Scenario controlled traffic - Specific actions of any of the traffic objects can be specified using a windows based GUI. • Operator controlled traffic - The operator can also take control of any traffic object.	**Other Features** • Transmission simulation type capabilities - Eaton / gate lockout, manual grinding feedback • Steering wheel bandwidth - 20 Hz • Operator capabilities - scenario editing, playback, scoring • Vehicle dynamics model - operator adjustable, including 3D tire model • Road data base - configurable data base including urban, rural, mountains, highway scenes

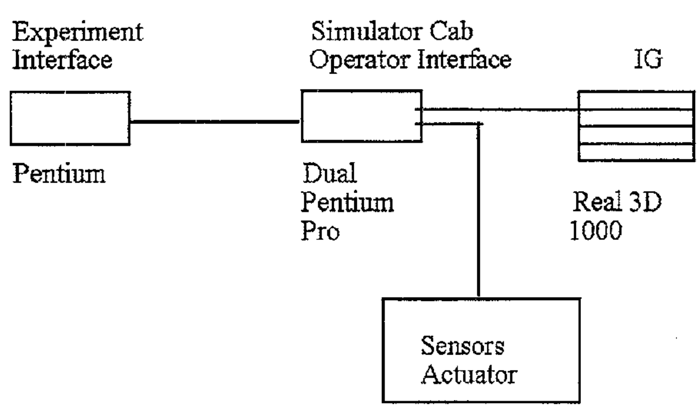

Figure 3. TruckSim® System Configuration

platform, and includes independent actuators for roll, pitch, surge and heave. All of the systems employed in the simulator are briefly outlined below in Table 3.

The system configuration for TruckSim® is shown in Figure 3. All simulator control and the operator interface are contained in a dual Pentium Pro PC, four Real 3D 1000 image generators are employed to generate the visual scene, a Pentium PC is employed for the experimenter's console. All sensors and actuators are integrated directly into the dual Pentium Pro. Communication among the systems is accomplished using a 100 baseT Ethernet.

Simulated nighttime drive scenario. The overnight, out-and-back drives, both control and feedback conditions were performed using the high-fidelity ISIM Mark II Mobile Driving Simulator, TruckSim® described above. Both feedback and control conditions used the same nighttime drive scenario. The drive consisted of a 21-mile looped freeway scenario with 2 and 3 lanes in each direction. Subjects had to drive this loop approximately 5 times on the outbound portion of the drive to complete 100 miles and approximately 5 times on the inbound portion of the drive to complete another 100 miles. The visual field for the subjects was 180° with high-resolution graphics. The scenario was programmed to include traffic that was typical of a night drive (i.e. direction of traffic, density of traffic and aggression of traffic). This interstate scenario also included multiple exits, rest area, flat test area, and runaway ramps. The simulator also included moving truck sounds and vibration to make the drive realistic. The simulator was instrumented with interior lights and high and low beam exterior lights.

PERCLOS Detection System

An automated, on-line, drowsiness detection system based on the duration of eyelid computer platform. PERCLOS values, based on the recorded eye closure measurements were calculated in real time without operator intervention. The PERCLOS monitor recorded eye closure based on the physiological property that the human retina reflects different amounts of infrared light at varying wavelengths. The retina reflects 90% of the incident light at 850 nanometers (nm), however, at 950nm, the intensity of reflection is sharply reduced due to the adsorption of the light by water molecules.

In order for the automated PERCLOS system, used in this study, to work properly, it required two equally illuminated images of the subject's face that differed in retinal reflection intensity: (1) one created with 850nm light and (Figure 4) and (2) one created with 950nm of light (Figure 5). Two separate cameras were required by the automated PERCLOS system in order to obtain these two identical images. One camera contained an 850nm filter and the other contained a 950nm filter. Both cameras were focused on the same point and were situated at a 90-degree angle to one another. The image was passed through a beam-splitter that transmitted or reflected the image onto the lenses of each camera. Due to the differences in retinal reflection intensity, the 850nm image could be subtracted from the 950nm image resulting in an isolated retinal reflection image (Figure 6). This subtraction process also eliminated any reflective glare that may have arisen from subject's glasses. The retinal image sizes were measured and the results were used to calculate PERCLOS values and this process was repeated ten times per second.

Technical components. The two main technical components in the automated PERCLOS system used in the current study consisted of the cameras and associated components required to

Pages 30 and 32 are missing in the master copy automated, on-line PERCLOS system used in the study that read the video images, processed the images and then generated eye closure values: (1) The first step was initialization which included identifying each frame grabber and assigning them to their corresponding PCI bus slots, and

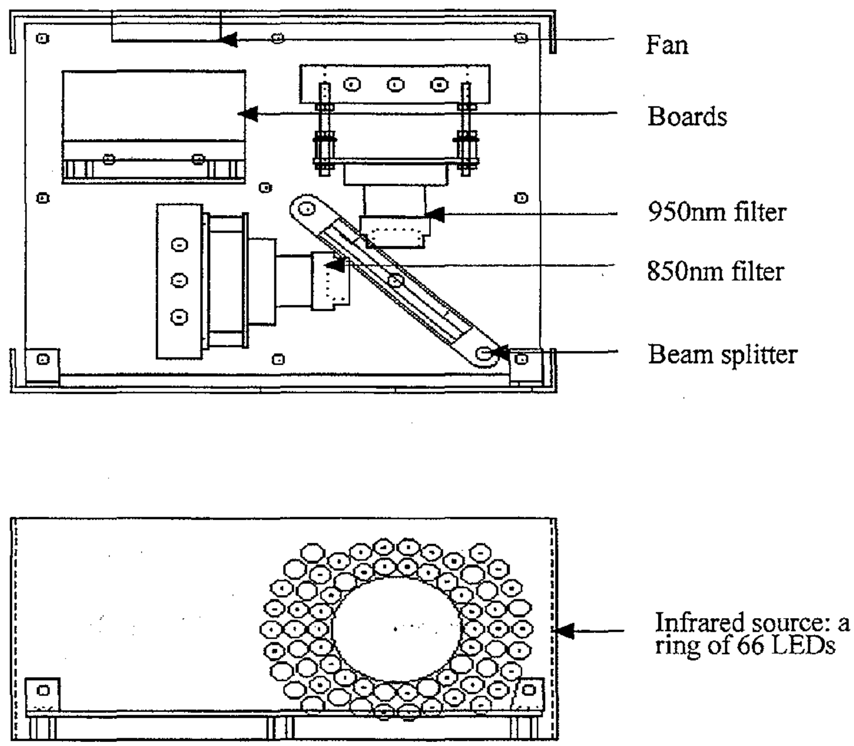

Figure 7. Instrumentation of PERCLOS monitor.

setting the correct image. (2) The next step was the frame grabbing process that stored in memory each of the images captured by the two cameras. (3) Image synchronization, which occurred in the third step, ensured that the frames were being processed from each camera lined up perfectly. This was necessary in order to guarantee that the correct images were being subtracted from one another. (Unsynchronized images, due to a mismatch between the 2 CCD cameras and synchronization circuitry, were rejected). (4) The fourth step was subtraction of the two images. Each pixel brightness value in the 950-image buffer was subtracted from each value in the 850-image buffer and the resulting image was stored in a subtraction buffer. (5) The fifth step was the bright-spot segregation routine that clustered all regions in the subtraction buffer that contained non-zero pixel values. This routine gathered all the bright pixels contained within a certain area, and then passed the values contained in each cluster to the extraction routine which determined whether the cluster is an eye, or noise. (6) Eye-image extraction occurred in the sixth step, which discriminated the image of the eye from surrounding noise. This was done by summing the pixel values of each cluster, and choosing the two largest clusters above a certain threshold. (7) The eye measurement routine calculated the height (i.e. degree of openness) of each eye, and stored the larger of the two values. (8)The process was finalized with the data storage routine. This routine stored the time and the calculated height of each observation in a

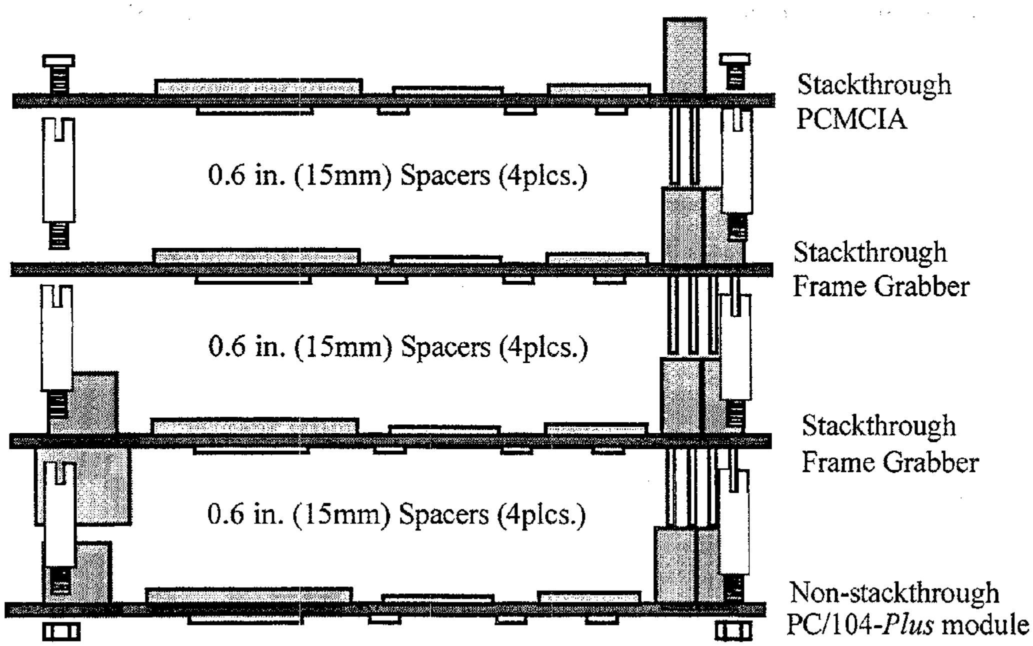

Figure 8. Hardware (PC/104 Stack) for PERCLOS monitor.

data file on the PCMCIA hard disk.

Driver Vehicle Interface

The PERCLOS driver vehicle interface system was used during the simulated nighttime drives in the feedback condition only. The system was designed with three levels of interaction between the system and the driver.

Level 1 – Visual Gauge: The function of the visual gauge was to give subjects, as determined by PERCLOS measurements, a real-time readout of their drowsiness. The visual drowsiness gauge was intended to: (1) provide a valid measure of drowsiness; (2) provide timely feedback to the subject regarding the result of self-alerting behaviors; and (3) provide a visual confirmation of the audible alarm.

Level 2 – Audible alarm: The function of the audible alarms is to gain the subjects attention and direct his attention to the gauge for visual confirmation of increasing drowsiness. The audible alarm was not intended to be an alerting stimulus.

Level 3 – Alerting Stimuli: The function of the alerting stimuli was to directly alert the subject and to direct his attention to the gauge for visual confirmation of sustained drowsiness.

Review of PERCLOS Validity. In past research, PERCLOS has been calculated over a defined time interval, typically 1-minute and 20-minutes. For the purposes of the driver feedback system, it was desirable to use shorter time periods typically between 1 and 6 minutes (Wierwille et al., 1998). However, it was necessary to assess the accuracy and validity of PERCLOS calculated over short time intervals before proceeding.

In a 1998 validation study, Dinges and colleagues (Dinges et al., 1998) experimentally tested the scientific validity of six alertness-drowsiness on-line technologies to predict a dynamic range of performance lapses and found that only PERCLOS, the video-based human-scored measurement of the proportion of time subjects had slow eye closures, was highly accurate in detection of the frequency of drowsiness-induced performance lapses while performing the Psychomotor Vigilance Test (PVT). It was also shown that PERCLOS was a better predictor of lapse duration or cumulative-time-in-lapse. The lapse duration criterion variable included very long-duration lapses (e.g., 10 sec to 30 sec duration) which may have prevented the PVT lapse frequency criterion from reflecting the true state of drowsiness as detected by one or more of the technologies /algorithms. Based on these results the correlation with PVT lapse duration was used to assess the validity of PERCLOS calculated over short time intervals. For PERCLOS calculated over a 1-minute interval (P1), the resulting correlation coefficient was 0.76. This value was considered sufficient to justify the use of PERCLOS calculated over a period of 1-minute or greater as the trigger for alarms and alerting stimuli or to be displayed on the visual gauge.

Driver vehicle interface design and application

Audible alarm. The design process began with the audible alarm to establish criteria for triggering an alarm and to select an appropriate sound. As mentioned above, the alarm was an indicator of increasing drowsiness. Hence, a threshold-based method was used to trigger the alarm. Two thresholds, T1 = 0.10 and T2 = 0.12, were applied to PERCLOS calculated over a three minute interval (P3) to trigger the alarm. The alarm was triggered when P3 increased through both thresholds. The dual threshold and P3 were employed to reduce the number of repeated alarms due to momentary fluctuations in the PERCLOS measurements.

The selected alarm sound was adapted from the 'ding' sound obtained from the Windows 98 operating system. (The ding.wav file is a standard wave file included with windows 98). The 'ding' sound is typically used by the Windows-98 operating system to indicate an error or to coincide to the display of an error message. The alarm sound consisted of playing the wave file "ding.wav" twice to get a 'ding-ding' sound that played for about 1 second.

The threshold T2 = 0.12 and the criteria variable, P3, were initially selected based on NHTSA sponsored research in this area (Wierwille et al., 1998) and direct conversation with Dr. Wierwille. The second threshold was added to further reduce the potential for multiple alarms due to momentary fluctuations in P3. These values were tested for appropriateness by applying them to PERCLOS data collected in a previous over-the-road study (Grace et. al., 1999). Several drowsiness episodes were selected for the evaluation. They included both rapid increases in drowsiness and gradual increases in drowsiness. The triggering algorithm was applied to these data that were in turn subjectively evaluated to assure that the alarms occurred while both P1 and P3 were increasing. From the subjective evaluation of these plots (see Figure 9) it was concluded that the algorithm did provide appropriate alarms for both rapidly and gradually incresing drowsiness episodes. It was also concluded that this algorithm effectively avoided repeated alarms due to momentary fluctuations in P3. It was also concluded that P1 was too noisy for use as the alarm criteria variable.

Visual Gauge. The visual gage was designed as two horizontal rows of 9 LED's (see figure 10). Each row was color coded to represent low drowsiness – green, moderate drowsiness

– yellow and extreme drowsiness – red. P1 was displayed on the upper row in order to provide the driver with timely feedback regarding his self-alerting behaviors. Since it was determined that P3 would be used to trigger alarms, P3 was displayed using the lower row of LED's to provide the drivers with a conformation of the audible alarm. For both gauges, each successive LED was lit when the displayed variable increased by 0.03. The P3 gauge was distinguished from the P1 gauge by lighting only one light. For Example if P3 = 0.12 only the fourth LED (first yellow LED) would be lit. The first three LED's (green LED's) would not be lit, while for the P1 gauge the first four LED's would be lit. Hence, P1 = 0.12 and P3 = 0.12 the gauge would appear as shown in Figure 10.

Although, this example uses equal values for P1 and P3, in practice these values are often different. Since P3 is calculated over a longer time period, P3 lags in time the value of P1. Hence, when P3 is rising through the alarm threshold P1 is often larger than P3. Conversely, when P3 is falling below the alarm threshold, P1 is often smaller than P3. Hence, the relative position of P1 and P3 on the gauge can give the subjects an indication of increasing or decreasing drowsiness.

The scale used in the visual gauge was chosen so that the first yellow LED corresponds to the alarm threshold. This was intended to inform the drivers that they were at the early stages of drowsiness.

Alerting stimuli. The alerting stimuli were intended to alert the driver when a high level of drowsiness was sustained. The alerting stimuli algorithm was designed to apply appropriate alarms for very rapid increases in drowsiness and for gradual increases in drowsiness. For consistency with the alarm triggers, P3 was used as the criteria variable. The alerting stimuli were delivered when P3 remained over a given threshold for a period of time. Multiple incresing threshold were used each paired with a corresponding decreasing delay time (see Table 4). If P3 remained over any given threshold for longer than the designated delay time an alerting stimulus was delivered. The delay time counters for all threshold values were reset when an alerting stimulus was delivered.

Table 4. Threshold and delay time used to trigger delivery of alerting stimuli.

Alert level	PERCLOS 3 threshold	Delay in seconds
1	0.10	120
2	0.13	90
3	0.17	60
4	0.20	45
5	0.25	30

The altering stimuli triggers were tested for appropriateness by applying them to PERCLOS data collected in a previous over-the-road study. The alerting stimuli triggering algorithm was subjectively evaluated to assure that the alarms occurred while P3 and P1 were still at high levels. From the subjective evaluation of these data (see Figure 9) it was concluded that the algorithm did provide appropriate timing of, the alerting stimuli for both rapidly and gradually incresing drowsiness episodes.

One of two alerting stimuli, depending on assigned condition, was delivered to the drivers. The olfactory alerting stimulus was a burst of peppermint scent & a buzzer sound. The buzzer sound had a central frequency of 4200 Hz. The buzzer sound was triggered for approximately 2-seconds. The peppermint scent lingered for approximately 10 – 15 seconds. The voice command was a female stating: " Warning, you are very drowsy. Take corrective action." The duration of the message was approximately 5-seconds.

Key Dependent Variables

PERCLOS based drowsiness metrics. Drowsiness levels were assessed using the automated PERCLOS system, measuring PERCLOS values minute-by-minute, and the cumulative time PERCLOS was above threshold (see section entitled "Development of multiple

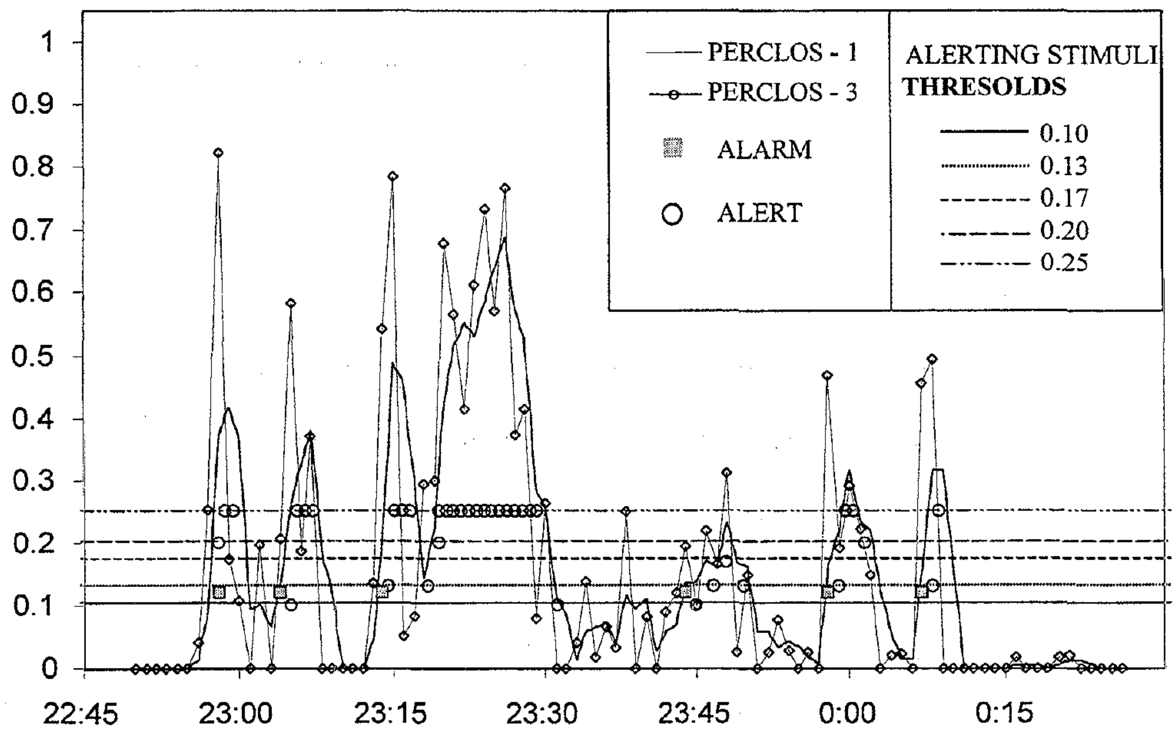

Figure 9. Over-the road data plotted together with triggers for alarms and alerting stimuli.

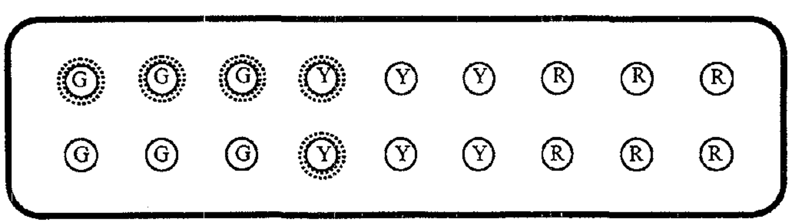

Figure 10. Visual gauge shown displaying P1 = P3 = 0.12.

threshold alarm/alert system"). PERCLOS-based drowsiness was also assessed by measuring the timing and administration of feedback alarms and alerting stimuli of either peppermint scent + buzzer or voice warnings. In examining the results of the study it is important to keep in mind that in the control condition, drivers were monitored with PERCLOS but did not receive feedback via a visual gauge or alarms or alerts. This permitted us to calculate their PERCLOS 1 and 3 minute values during control drives, as well as the number of alarms and alerts they ***would have received*** had the feedback been provided. Thus the number of control condition alarms + alerts or the number of control condition alerts shown in later figures refers to those the subject would have received in the control condition, based on the PERCLOS 1 and 3 minute threshold/algorithm (which was identical between the feedback and control conditions).

Driving performance. Driving performance was assessed using automated driving variables recorded from the TruckSim® simulator. These included the standard deviation of lane position; the number of lane departures per minute; the standard deviation of steering wheel velocity; and the number of collisions.

Driver behaviors. Rest breaks were assessed using behavioral observation of the timing, duration and activity taken during breaks. Subjects were permitted to determine the timing and duration of their rest breaks, with the exception of the rest break at the midpoint of the nighttime drive (i.e., at the turn-around point), which was predetermined by protocol. A continuous record was also kept of subject's voluntary behaviors in the cab while driving (e.g. postural changes, rubbing face, head nodding, yawning, smoking, etc.).

STATISTICAL APPROACH

OUTCOME VARIABLE DEFINITIONS

Three classes of outcome variables were examined. These classes are distinguished on the basis of how the minute by minute data were summarized within leg (outbound leg versus inbound leg) and condition (feedback versus no feedback). The three classes were defined based on mean values; changes over time (slopes), and total number of events or total numbers of minutes in which certain events took place.

Within Leg Summary Mean Values

Minute-specific interval variables included 1 minute PERCLOS, a 3 minute running average PERCLOS and a number of driving performance measures (e.g., standard deviation of lane position within 1 minute, number of lane changes within 1 minute, average speed over 1 minute, and number of lane departures). Leg specific summary mean values were computed for all interval variables.

Within Leg Average Changes Over Time (Slopes)

Two-stage random effects regression analyses (Feldman, H.A., 1988, Gibbons et. al., 1988) were used to assess changes in performance over the course of each leg for two primary interval variables, 3-minute PERCLOS and the standard deviation of lane position. In this method, subject to subject variation in the effects of leg (outbound verses inbound) and feedback status (present versus absent) is explicitly recognized. The first stage of analysis consisted of obtaining least squares estimates of simple linear regression slopes for each subject. These slopes were interpreted as subject-specific estimates of average changes (per unit time).

The second stage of analysis consisted of analyzing the slopes using the descriptive and mixed model ANOVA procedures described below.

Within Leg Total Number of Events or Total Number of Behavioral Minutes

The total number of alerts, total number of alarms, and total number of minutes in which either an alert or a alarm occurred were computed within each leg. Similarly, the total numbers of each recorded behavior were computed. Recorded behaviors included facial changes, head rolls, head nods, hitting face, neck/shoulder rubs, postural changes, rubbing eyes, rubbing face, scratching face, squinting, stretching, yawning, taking a beverage, having a cigarette, eating food, moves cap, adjusts glasses, and miscellaneous others. The total number of a specific behavior exhibited in any one minute was computed and then summed over each leg for each subject to produce a count of the total number of a specific behavior per leg. This allowed for the identification of single behaviors as well as multiple behaviors within each minute. An indicator variable (1 = behavior, 0 = no behavior) was constructed to identify whether in each minute any specific behavior occurred. Indictor variables were summed for each leg to produce a measure of *behavioral-minutes*, that is, the total number of minutes in which any behavior occurred.

Primary Outcome Variable

In order to reduce the Type I error rate, three variables were selected as primary. There variables included 1) the mean lane change standard deviation, 2) the mean 3- minute PERCLOS running average, and 3) the total number of minutes in which there was either an alert or an alarm. These variables were selected prior to performing formal analyses. All other outcome variables were analyzed similarly but the results were interpreted as secondary or hypothesis generating.

ANALYSIS PARADIGMS

Four analysis paradigms were used to structure the data analyses. The first paradigm focused on the overall effect of feedback on the driving and sleepiness outcome variables. The second investigated potential differences between auditory and olfactory feedback. The third examined whether the effect of feedback (present versus absent) depended upon whether a subject received the feedback first and then the control condition compared to undergoing the control condition first and then the feedback condition. The fourth analysis paradigm focused on the timing of alerts and alarms. In this analysis, we defined a segment of event-free minutes as the number of minutes between the occurrence of either an alert or an alarm until the next occurrence of either an alert or an alarm. Descriptive analyses involved modifying the definitions of the time between events before considering a subsequent alert or alarm as belonging to a new sequence.

Overall Effect of Feedback

Descriptive analysis. Descriptive analyses were performed for each primary and secondary variable. Tables of cell means were constructed that displayed mean response values for the feedback condition compared to the no feedback condition. This was done for the whole trip and by leg (outbound verses inbound). Primary attention was paid to the cell means stratified by leg. Mean values for within subject differences were also summarized. These included:

1. Differences between inbound and outbound legs within condition;
2. Differences between the feedback and no feedback conditions within leg; and
3. Differences between the inbound and outbound legs in the differences between feedback conditions.

Standard deviations and p-values derived from paired t-tests (df = 15) were displayed for each of the three types of differences described above. The third type of difference (i.e. the difference of differences) produces a paired t-test that is mathematically equivalent to the test for leg-by-feedback interaction obtained from the mixed model ANOVA described below. In addition, median values, minimum and maximum values, and percent changes were displayed. The median, minimum and maximum values were used to further summarize the distributions. The percent changes were used in some cases as a convenient way to compare effect sizes across outcome measures. However, for some outcome measures and for most differences variables, denominator values close to zero resulted in large extreme values limiting the usefulness of percent change summaries.

Paired t-tests for differences were repeated using non-parametric Wilcoxon signed-rank tests to confirm that results were robust against departures from normal distributions. The resulting Wilcoxon p-values were generally very similar to the paired t-test p-values and so only paired t-test results are summarized.

Mixed model analysis of variance. Mixed model analysis of variance (ANOVA) was used to construct all formal significance tests for primary and secondary outcome measures. The mixed model contains parameters used in linear contrasts representing experimental factors of interest such as feedback compared to no feedback and outbound leg compared to inbound leg. In addition, the mixed model contains parameters representing between-subject variance among outcome measures. The total between subject variance is comprised of components. In addition to the usual residual or error variance, the models included three other variance components. These variance components included subject, subject by feedback, and subject by leg. The subject-by-feedback and subject-by-leg are random interactions reflecting between-subject variability in subject responses to feedback and between-subject variability in subject deterioration experienced in the second (inbound) leg compared to the first (outbound) leg. The relative magnitudes of the variance components were examined as a ratio or proportional difference relative to the size of the residual error and as a percentage of total variance. Approximate tests for significance were obtained for each variance components. The null hypothesis for these tests is that the specific variance component value is zero. The alternative hypothesis is that the variance component has some positive value.

Because of the special interest in the magnitudes of the variance components, analysis of variance models were estimated using the technique *of restricted maximum likelihood* (Diggle et. al., 1996) (REML) as implemented in the SAS procedure PROC Mixed (Proc Mixed, SAS/STAT Software, 1997). Maximum likelihood approaches have theoretical advantages over least squares approaches. Of particular importance, for this study is that least squares estimates of variance may be negative while maximum likelihood estimates cannot be negative. In many instances, the statistical tests for fixed effects produced by these two approaches are identical. For example, the test for leg-by-feedback interaction produced by the REML mixed model is numerically equivalent to the paired t-test described above for the differences between differences.

Comparisons Between Auditory and Olfactory Feedback

Descriptive analysis. The second analysis paradigm explicitly recognized and compared types of feedback. Eight subjects received auditory feedback and eight subjects received olfactory feedback during the outbound leg. Thus, during the outbound leg feedback type is a between-subjects factor. Similarly, during the inbound leg, eight subjects received auditory feedback and eight subjects received olfactory feedback. Subjects receiving auditory feedback during the first leg received olfactory during the second and vice-versa. Descriptive analysis focused on comparing mean values between the 8 subjects receiving auditory feedback during the outbound leg to the 8 subjects receiving olfactory and between the 8 subjects receiving auditory during the second leg to the 8 subjects receiving olfactory. Descriptive paired t-tests (df = 7) were performed for the effects of auditory stimuli and for the effects of olfactory stimuli separately for the outbound and inbound legs. Student's pooled t-tests for independent samples were used to produce descriptive comparisons of the mean feedback minus control conditions between auditory and olfactory feedback. This was done separately for the outbound and inbound legs.

Mixed model analysis of variance. The mixed models for type of feedback including the following fixed effects: leg (outbound versus inbound), condition (feedback provided versus feedback hidden), feedback type (auditory versus olfactory), leg by feedback type interaction, leg by condition interaction, feedback type by condition, and leg by feedback type by condition interaction. Random effects included subject, subject-by-condition, and subject-by-leg interaction. Of primary concern, were the feedback-type by feedback-condition interaction and the leg-by-feedback type by feedback-condition interaction. The feedback-type by feedback-condition represents differences between the auditory and olfactory model in terms of feedback effectiveness. The leg by feedback-type by feedback-condition interaction term was used to examine whether such differences varied systematically by leg.

Analysis of Order Effects

The mixed model for the analysis of order effects introduced a between subjects fixed effect comparing the $n = 8$ subject given the sequence of control/feedback to the $n = 8$ subjects given the sequence of feedback/control. This effect was tested with an F-statistic with $df = 1,14$. Other fixed effects included the main effect of feedback condition (present versus absent, $df = 1,14$); the main effect of leg (outbound versus inbound, $df = 1,15$); leg-by-feedback interaction ($df = 1,15$); and order-by-feedback interaction ($df = 1,14$). Random effects included subject nested within order, subject-by-feedback nested within order and subject by leg nested within order. The primary effect of interest was the order by feedback interaction. We wished to confirm that assessments of feedback present versus feedback absent did not depend on the experimental sequence. If the order-by-feedback interaction is not significant, we may ignore the effect of order in the two sets of analyses described above without introducing bias.

RESULTS

Fidelity of Driving Simulation

Drivers perceived the TruckSim® full-motion simulator and the programmed night drive on a divided highway with relatively little traffic as realistic. All 16 of the regular nighttime drivers rated the realism of the scenario after each drive (i.e., 32 ratings)—95% of these ratings were positive for a realistic driving scenario. Drivers also took the driving task very seriously. There were no single or multi-vehicle crashes, other than a few during the drives of the initial subjects, when simulator malfunction led to the sudden appearance of a stopped vehicle in the truck's lane. All drivers also completed their outbound and return (inbound) drives during both control (no feedback) and PERCLOS feedback conditions within the time limits required by the protocol. Consequently, the TruckSim® driving simulation was perceived as having real-world fidelity and was responded to by drivers in a realistic manner.

Sleep Need and Circadian Timing of Drives

Actigraphic and sleep log data revealed that drivers slept comparable amounts prior to control (no feedback) and PERCLOS feedback conditions. This was the case the night before each condition (feedback $M = 7.62$, control $M = 7.15$; $t = -0.96$, $p = 0.35$), as well as the average of 3 nights before each condition (feedback $M = 7.47$, control $M = 7.17$; $t = -0.89$, $p = 0.39$). Consequently, there was no evidence that sleep drive was elevated more for either the control or feedback condition. Control and feedback conditions also occurred at times of day that were not significantly different (feedback drive start time M = 6:54a.m, control drive start time M = 6:30a.m; $t = 1.06$, $p = 0.30$). Therefore, there was no evidence of differential time-of-day influences on drowsiness during the control and feedback drives. Any differences in drowsiness outcomes, driving variables, or drivers' behaviors between control and feedback conditions, would not, therefore, be likely to be due to different degrees of sleep need or circadian time of drives.

Order of Conditions

The within-subjects study design involved counterbalancing the order in which subjects drove the control (no feedback) and feedback conditions, as well as the order of voice and olfactory alerts during the feedback drives. The counterbalancing was intended to average across control and feedback conditions, the effects of learning to use the TruckSim® simulator and adaptation to the driving scenario. Order-by-feedback interactions with feedback conditions were tested by ANOVA and were not significant in the analyses of outcome variables. Consequently, order of conditions did not affect the impact of feedback vs. no feedback on outcomes. Therefore order of conditions was not considered in all subsequent results reported.

Outbound vs. Inbound Drives

Virtually all PERCLOS drowsiness metrics revealed, as expected, that drivers were sleepier during the second driving leg (inbound or return leg) of the control and feedback trips than they were on the outbound legs. This was expected based on the increased prior wake time of the inbound drive relative to the outbound drive. Main effects for drive leg (outbound vs. inbound) were significant in the ANOVAs for PERCLOS 1 minute and 3 minute ($p = 0.002$); the number of alarms and alerts ($p = 0.003$); the standard deviation of lane position ($p = 0.017$); and the number of behaviors engaged in by drivers to promote alertness ($p = 0.005$). However, as described below, there were also significant interactions between drive leg and feedback for some of these variables, suggesting that PERCLOS feedback had greater effects during the drowsier inbound (return) drive.

Feedback vs. No Feedback

Effects of feedback vs. no feedback on drowsiness. Providing PERCLOS feedback to drivers tended to reduce drowsiness, especially on the inbound drive, when drowsiness was greatest. Figures 11, 12, 13, and 14 reveal these ANOVA interaction effects. This interaction effect was a trend for the mean of PERCLOS 1 minute (Figure 11, $p = 0.092$). It reached statistical significance for the number of alarms + alerts (Figure 12, $p = 0.04$), and the number of voice + olfactory alerts (Figure 13, $p = 0.024$). There was also a trend present in the results for the slope across drive of PERCLOS 3 minute (Figure 14, $p = 0.073$), which refers to the steady increase in PERCLOS 3 levels (i.e., greater drowsiness) as the inbound drive progressed. This steady increase in PERCLOS 3 levels as the inbound drive progressed was markedly reduced in the feedback condition relative to the control condition.

Between subjects differences in PERCLOS drowsiness measures. There were substantial individual differences present in the magnitude of drowsiness during both feedback and control drives. As described in the Statistical Approach section (above) the mixed model ANOVA used to assess experimental effects also contained parameters representing between-subject variance among outcome measures. In addition to the usual residual or error variance, the models included subject by feedback and subject by leg random interactions reflecting between-subject variability in responses to feedback and between-subject variability in deterioration experienced in the second (inbound) leg compared to the first (outbound) leg. Subject by leg random interactions were not statistically significant for PERCLOS variables, indicating that all subjects tended to be drowsier on the inbound drive than on the outbound drive. However, the

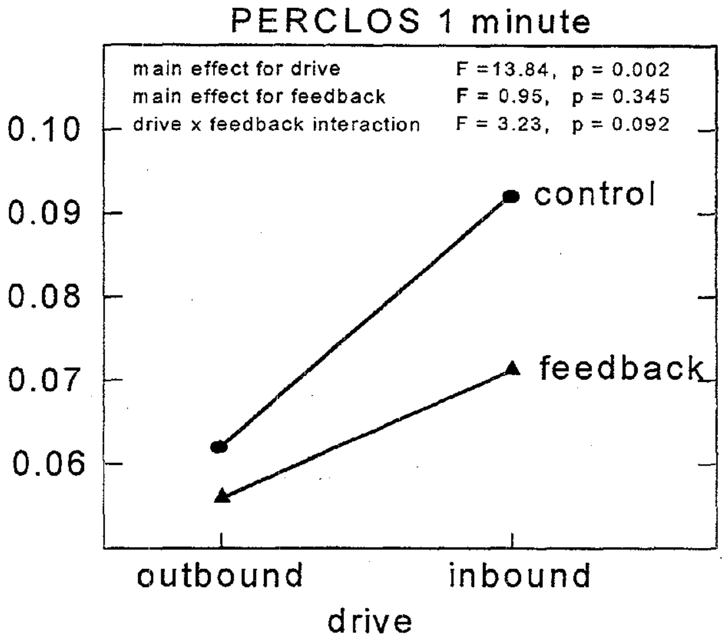

Figure 11. Effects of PERCLOS feedback (via visual gauge + auditory alarm and alerts) versus no feedback (control condition) on 1 minute PERCLOS values during the outbound and inbound portions of the nighttime drive. Higher values indicate greater drowsiness. Mixed model ANOVA results for drive and feedback and their interaction are displayed in the upper portion of the graph.

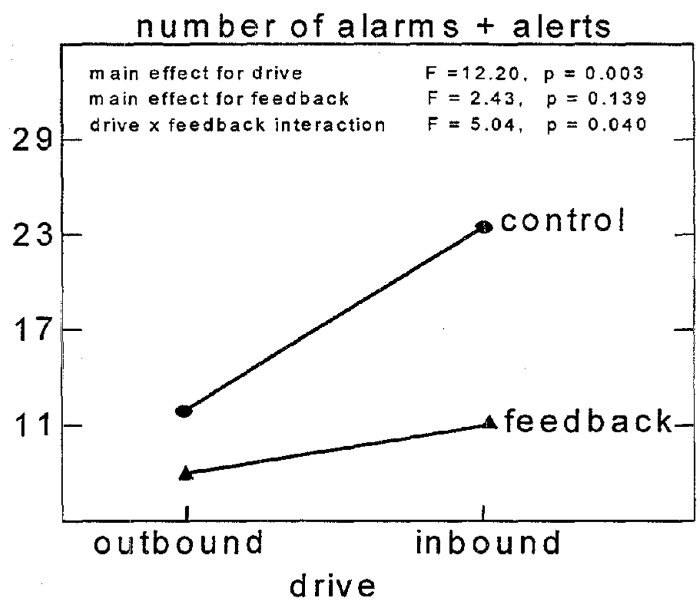

Figure 12. Effects of PERCLOS feedback (via visual gauge + auditory alarm and alerts) versus no feedback (control condition) on the number of alarms + alerts delivered to subjects during the outbound and inbound portions of the nighttime drive. Higher values indicate greater drowsiness. Mixed model ANOVA results for drive and feedback and their interaction are displayed in the upper portion of the graph.

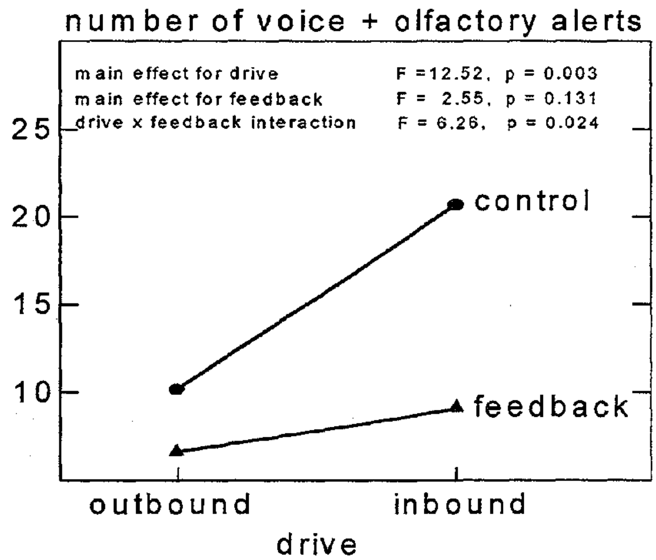

Figure 13. Effects of PERCLOS feedback (via visual gauge + auditory alarm and alerts) versus no feedback (control condition) on the number of voice + olfactory (peppermint + buzzer) alerts delivered to subjects during the outbound and inbound portions of the nighttime drive. Higher values indicate greater drowsiness. Mixed model ANOVA results for drive and feedback and their interaction are displayed in the upper portion of the graph.

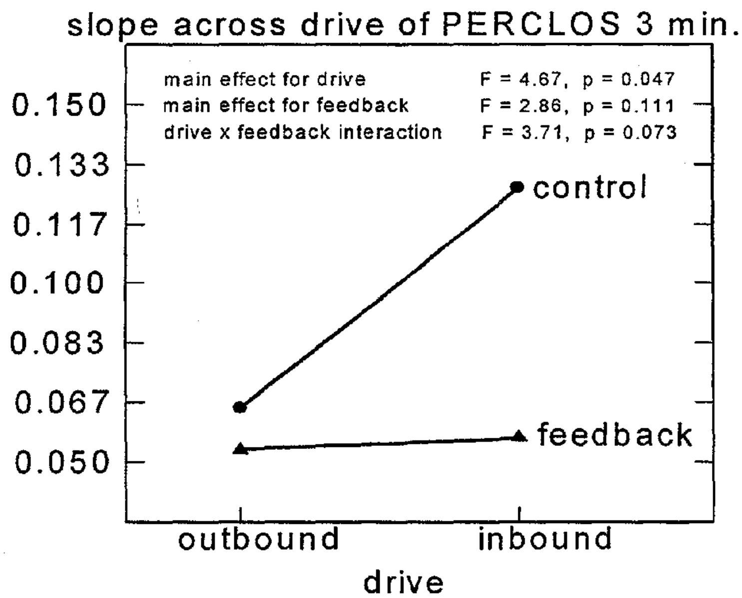

Figure 14. Effects of PERCLOS feedback versus no feedback on the slope across the drive of PERCLOS 3 minute during the outbound and inbound portions of the nighttime drive. Higher values indicate greater drowsiness. Mixed model ANOVA results for drive and feedback and their interaction are displayed in the upper portion of the graph.

subjects-by-feedback random interactions were significant (PERCLOS 1 minute, $p = 0.014$; PERCLOS 3 minute, $p = 0.014$; number of alerts, $p = 0.015$). The relative magnitudes of these between-subjects variance components were examined as a ratio or proportional difference relative to the size of the residual error and as a percentage of total variance. In all cases, between-subject variance accounted for 28% - 29% of the residual variance.

The large between-subject variance in PERCLOS-measured drowsiness was evident in the distribution of the total number of alarms and alerts across both feedback and control conditions combined. Figure 15 displays a histogram of these totals. As is evident in the figure, three drivers never achieved a drowsiness level that warranted an alarm or alert (i.e., total = 0). In contrast, three other drivers had cumulative totals of alarms and alerts in excess of 100.

As discussed above, PERCLOS feedback (but not drive leg) interacted with the between-subject variance in drowsiness level. Table 5 shows the number of subjects who had lower levels of drowsiness over both drives (i.e., total alarms + alerts ≤ 40) compared to those with higher levels of drowsiness over both drives (i.e., total alarms + alerts > 40). It's clear that PERCLOS feedback had a beneficial effect in reducing drowsiness in most (71%) subjects who had higher levels of drowsiness (total alarms + alerts > 40), but it affected a smaller proportion (33%) of those drivers who had lower levels of drowsiness (total alarms + alerts ≤ 40).

Effects of feedback vs. no feedback on driving performance. Paralleling the effects on PERCLOS alertness-drowsiness measures, providing PERCLOS feedback to drivers tended to improve driving performance, especially on the inbound drive, when drowsiness was greatest. Figures 16, 17, 18, and 19 display these ANOVA interaction effects. Only the number of lane

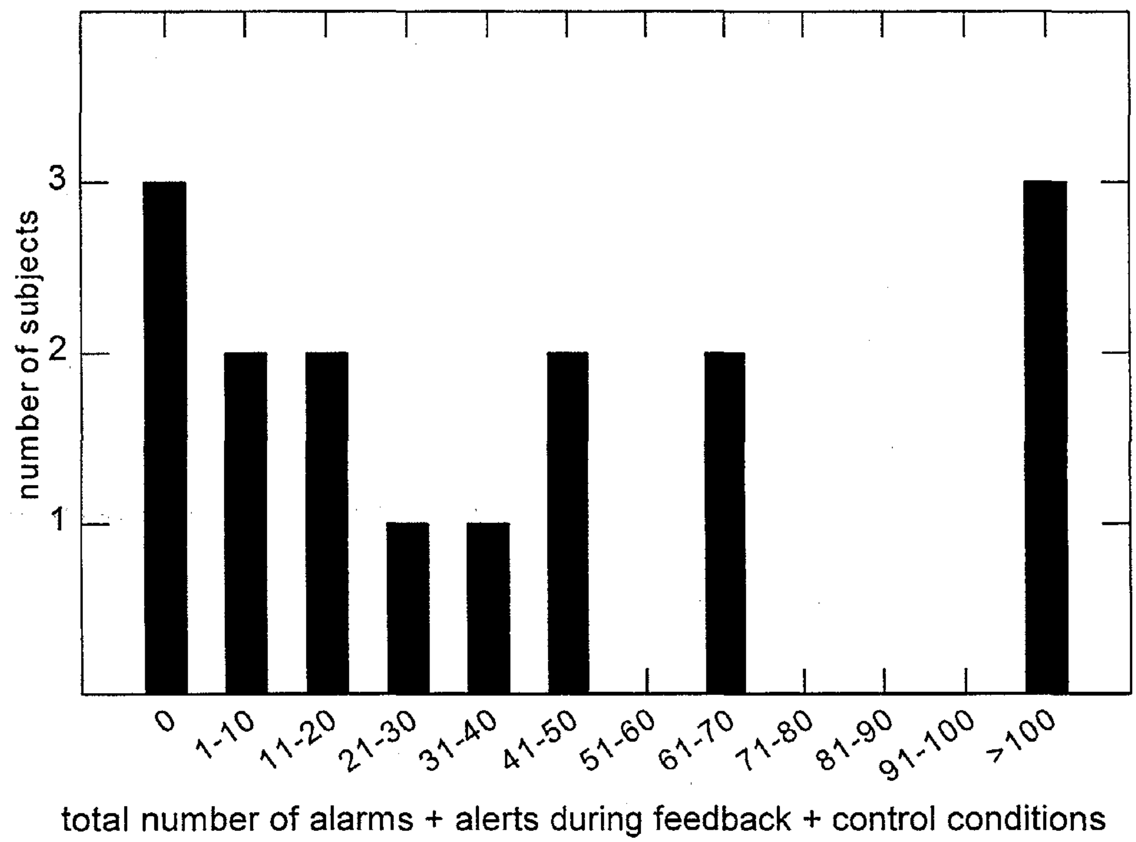

Figure 15. Histogram of the distribution of subjects based on the total number of alarms and alerts across both feedback and control conditions combined. Three drivers never achieved a drowsiness level that warranted an alarm or alert (i.e., total = 0). In contrast, 3 other drivers had cumulative totals of alarms and alerts in excess of 100.

Table 5. Number of subjects who received more alarms and alerts in the feedback conditions versus more in the control condition, versus the same number in each condition, as a function of total number of alarms and alerts.

	Feedback < Control	Feedback > Control	Feedback = Control
Total alarms + alerts $\leq$ 40	**3**	**3**	**3**
Total alarms + alerts > 40	**5**	**2**	**0**

departures per minute (Figure 16) reached significance for the drive-by-feedback interaction ($p = 0.036$). ANOVAs on the other driving variables yielded trends for main effects for feedback. This included the standard deviation of lane position (Figure 17, $p = 0.076$) and the slope across drive of lane position standard deviation (Figure 18, $p = 0.064$), as well as for the standard deviation of steering wheel velocity (Figure 19, $p = 0.082$). Although drivers' average speeds were analyzed, these data were deemed unreliable owing to a malfunction of the TruckSim's® speed tracking software.

Effects of feedback vs. no feedback on drivers' behaviors. Out of $n = 16$ drivers and four 1.67 hr drive legs each (64 drive legs), no driver took a break for rest purposes, and only 5 drivers took any breaks—all of which were for personal hygiene and of a duration less than 3 minutes. Therefore, despite the occurrence of rest breaks being a focus of the experiment as a key outcome variable, they did not occur in either control or feedback conditions. However, behaviors of drivers while driving (e.g. postural changes, rubbing face, head nodding, yawning, smoking, etc) were carefully logged by an observer (via a video camera) in all conditions. These variables were analyzed separately and in aggregate. The results were similar to those observed for PERCLOS drowsiness variables and driving variables. Drive leg had a significant main effect on the following behaviors, in the direction of increased activity during the inbound leg when drivers were drowsier: total behaviors ($p = 0.0008$); yawning ($p = 0.03$); smoking ($p = 0.068$); chewing gum and food ($p = 0.06$); and vocalizations ($p = 0.017$). PERCLOS feedback to drivers also tended to increase drivers' behaviors (main effects) in the following areas: stretching ($p = 0.034$); rubbing face ($p = 0.062$); rubbing neck and shoulders ($p = 0.075$); and total behaviors ($p = 0.10$).

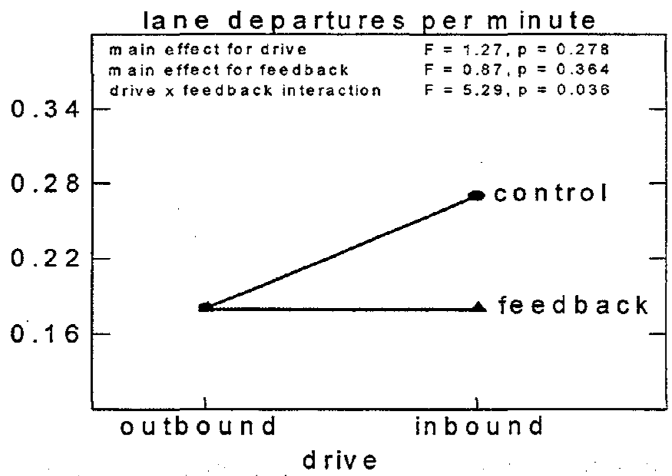

Figure 16. Effects of PERCLOS feedback (via visual gauge + auditory alarm and alerts) versus no feedback (control condition) on the number of lane departures per minute during the outbound and inbound portions of the nighttime drive. Higher values indicate greater driving variability. Mixed model ANOVA results for drive and feedback and their interaction are displayed in the upper portion of the graph.

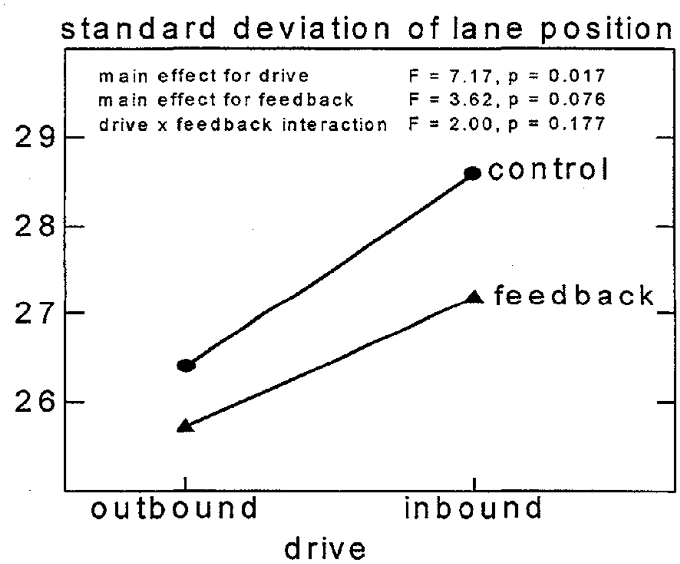

Figure 17. Effects of PERCLOS feedback (via visual gauge + auditory alarm and alerts) versus no feedback (control condition) on the standard deviation of lane position during the outbound and inbound portions of the nighttime drive. Higher values indicate greater driving variability. Mixed model ANOVA results for drive and feedback and their interaction are displayed in the upper portion of the graph.

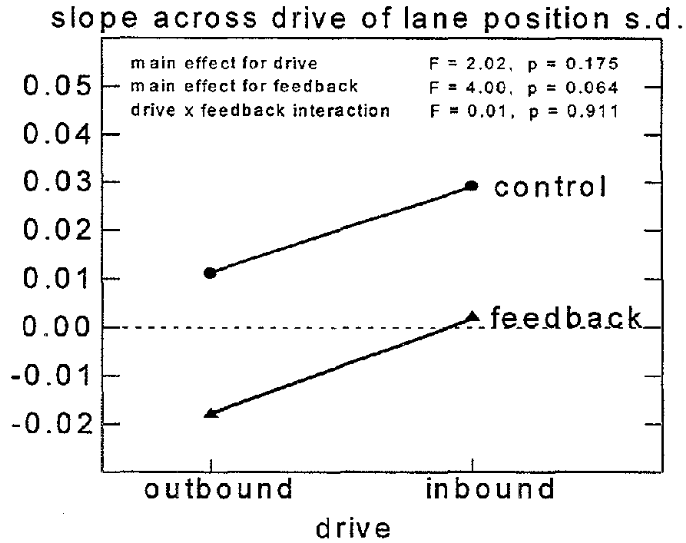

Figure 18. Effects of PERCLOS feedback (via visual gauge + auditory alarm and alerts) versus no feedback (control condition) on the slope across drive of the lane position standard deviation during the outbound and inbound portions of the nighttime drive. Higher values indicate greater driving variability. Mixed model ANOVA results for drive and feedback and their interaction are displayed in the upper portion of the graph.

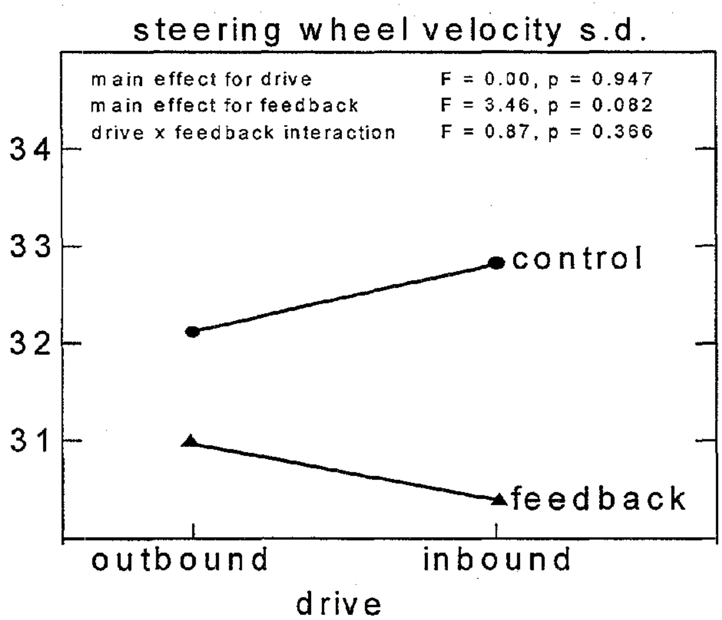

Figure 19. Effects of PERCLOS feedback (via visual gauge + auditory alarm and alerts) versus no feedback (control condition) on the steering wheel velocity standard deviation during the outbound and inbound portions of the nighttime drive. Higher values indicate greater driving variability. Mixed model ANOVA results for drive and feedback and their interaction are displayed in the upper portion of the graph.

The latter is shown in Figure 20. Only postural changes in the seat while driving showed a significant interaction between drive leg and feedback condition ($p = 0.038$), such that more postural changes occurred when feedback was present during the inbound (return) drive. Figure 21 displays this effect. In a separate analysis we examined whether behaviors were more likely to occur during times when feedback was present compared to times when feedback was not present. The detailed results of these analyses are presented in the appendix to this report.

Alerts: Voice vs. Peppermint + Buzzer Warnings

Analyses comparing the effects of the PERCLOS feedback voice alert versus the peppermint + buzzer alert were necessarily limited to those subjects who had both alerts. Moreover, the large between-subject variability in warning alerts (see Figure 15) also served to

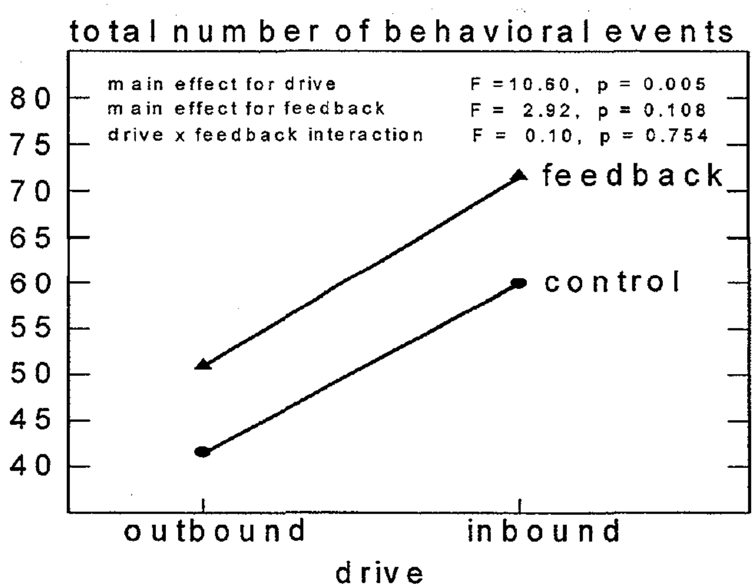

Figure 20. Effects of PERCLOS feedback (via visual gauge + auditory alarm and alerts) versus no feedback (control condition) on the total number of behavioral events during the outbound and inbound portions of the nighttime drive. Higher values indicate greater numbers of behavioral events. Mixed model ANOVA results for drive and feedback and their interaction are displayed in the upper portion of the graph.

reduce the power of statistical comparisons. These caveats notwithstanding, there was a trend for a significant interaction for PERCLOS 3 minute ($p = 0.052$) in the effects of feedback with feedback type (voice vs. peppermint), which is shown in Figure 22. Relative to peppermint + buzzer alerts, voice alerts appeared to have reduced PERCLOS 3 minute when feedback was provided to drivers. However, in the case of some other drowsiness variables, olfactory + buzzer alerts tended to have somewhat greater effects than voice alerts during the feedback outbound drive leg. Therefore differential effects from the two types of warning alerts were limited.

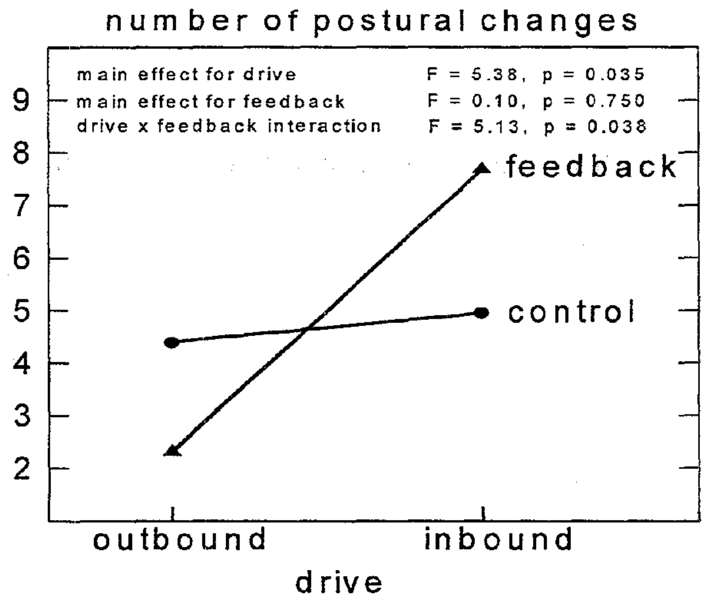

Figure 21. Effects of PERCLOS feedback (via visual gauge + auditory alarm and alerts) versus no feedback (control condition) on the total number of postural changes during the outbound and inbound portions of the nighttime drive. Higher values indicate greater numbers of postural changes. Mixed model ANOVA results for drive and feedback and their interaction are displayed in the upper portion of the graph.

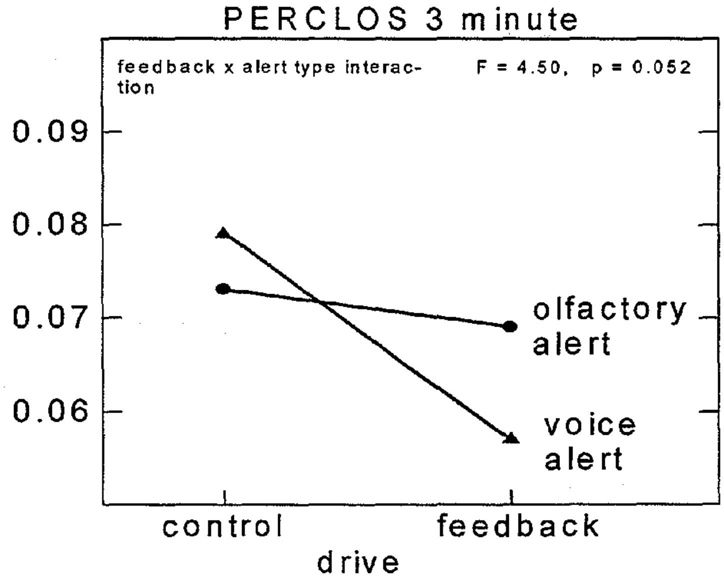

Figure 22. Effect on PERCLOS 3 minute values of feedback with voice alerts versus feedback with peppermint + buzzer alerts, versus no feedback (control condition). Higher values indicate greater drowsiness. Mixed model ANOVA results for the interaction of feedback condition by type of alert warning are displayed in the upper portion of the graph.

Drivers' Subjective Ratings of Sleepiness and PVT Performance

Prior to each drive beginning, at the mid-drive break, and after the final (inbound) drive in both feedback and control conditions, drivers rated their sleepiness on a visual analog scale immediately prior to and following a 10-minute PVT performance test. Results of analyses of these ratings and lapses on the PVT test showed that subjects felt progressively more sleepy from pre-drive to mid-drive to post-drive in both conditions (main effect for time on pre-PVT sleepiness rating, $p = 0.022$; main effect for time on post-PVT sleepiness rating, $p = 0.003$), and they had increasing numbers of PVT lapses from pre-drive to post-drive (main effect for time on PVT lapses, $p = 0.003$). These results are displayed in Figures 23, 24, and 25, respectively. Having driven with PERCLOS feedback differentially reduced drivers' pre-PVT sleepiness ratings (Figure 23, feedback by time interaction $p = 0.038$), but had no main effect or interaction

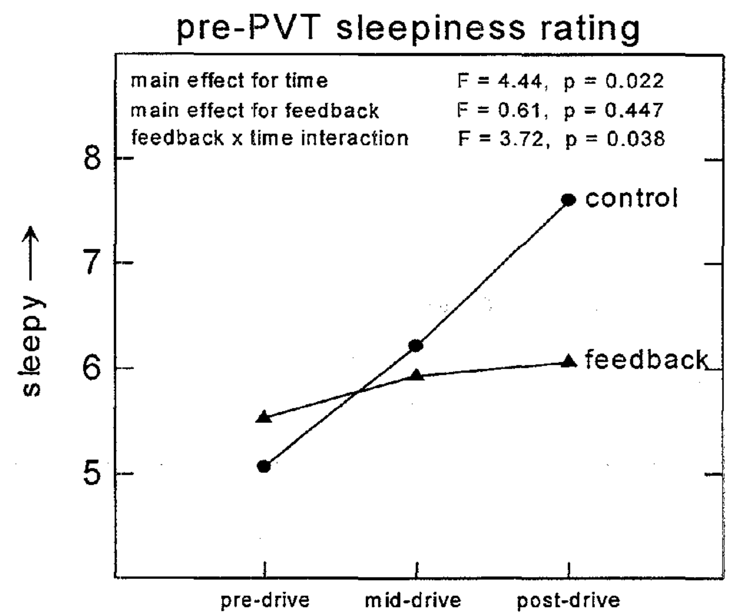

Figure 23. Effects of PERCLOS feedback versus no feedback (control condition), and time of drive (pre, mid, post), on drivers' sleepiness ratings (visual analog scale) immediately prior to completing a 10-minute PVT performance test. Mixed model ANOVA results for time and feedback and their interaction are displayed in the upper portion of the graph.

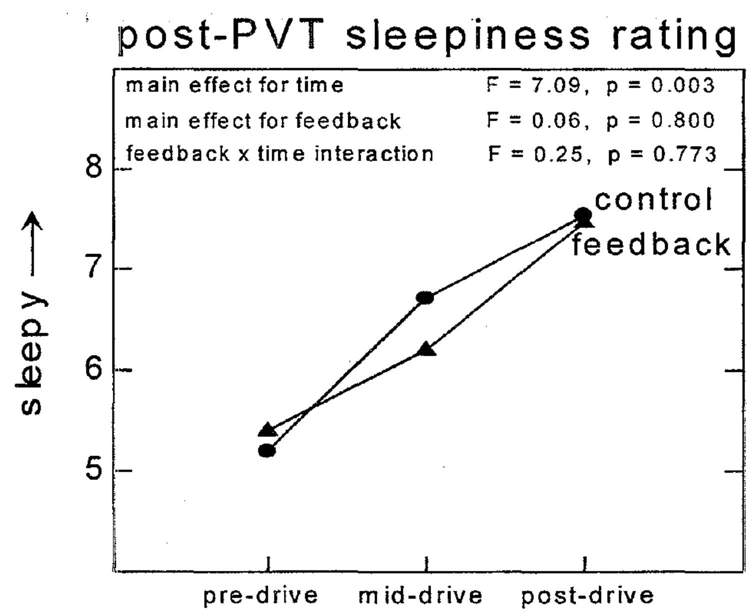

Figure 24. Effects of PERCLOS feedback versus no feedback (control condition), and time of drive (pre, mid, post), on drivers' sleepiness ratings (visual analog scale) immediately after completing a 10-minute PVT performance test. Mixed model ANOVA results for time and feedback and their interaction are displayed in the upper portion of the graph.

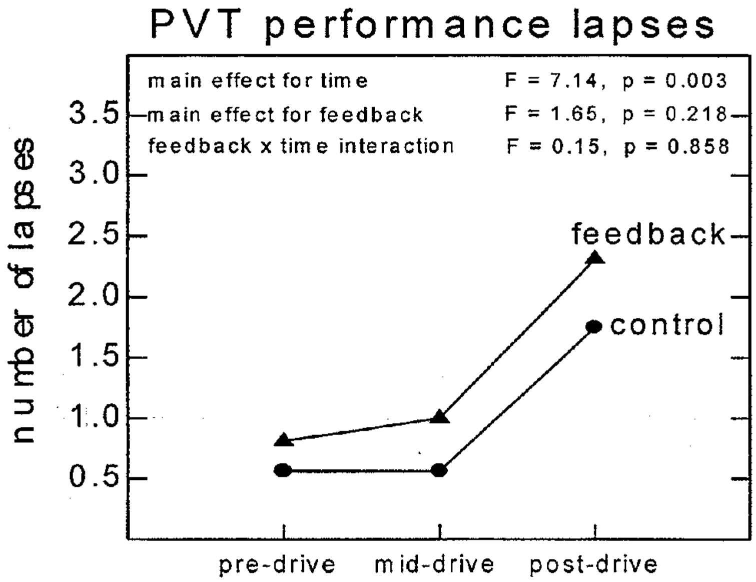

Figure 25. Effects of PERCLOS feedback versus no feedback (control condition), and time of drive (pre, mid, post), on PVT lapse frequency during a 10-minute PVT performance test. Mixed model ANOVA results for time and feedback and their interaction are displayed in the upper portion of the graph.

with time on either post-PVT sleepiness ratings (Figure 24) or PVT lapses (Figure 25).

Drivers' Perceptions of PERCLOS Feedback

Post-experimental inquiry surveys completed by drivers are summarized in Table 6 and revealed that in general drivers felt that PERCLOS feedback affected, predicted, and helped their tested (i.e., visual gauge + tonal alarm + voice or peppermint + buzzer alerts) tended to (1) reduce PERCLOS measures of drowsiness (both on average and as a function of time on task alertness/drowsiness. However, these ratings were not unanimously positive, and few drivers responded to questions about the voice alerts. It is important to remember, however, that not all drivers received voice alerts because their drowsiness levels (as assessed by PERCLOS) did not reach levels that would trigger warning alerts.

Table 6. Percentage of drivers who gave positive responses on a post-experimental survey regarding the effects of each modality of PERCLOS feedback.

Feedback type	...affect your alertness/ drowsiness level?	...accurate in predicting your alertness/drowsiness?	...help your alertness/ drowsiness level?
Visual gauge	77% (n = 13)*	57% (n = 14)	57% (n = 14)
Auditory alarm	90% (n = 10)	88% (n = 8)	86% (n = 7)
Voice alert	75% (n = 4)	50% (n = 4)	60% (n = 5)
Olfactory alert	50% (n = 10)	55% (n = 9)	66% (n = 9)

*number of drivers who responded to the question on the survey.

DISCUSSION AND CONCLUSIONS

There were reasonably consistent effects of PERCLOS feedback on five domains of outcome variables. Relative to the no-feedback (control) condition, the PERCLOS feedback system we [slope across the drive]; (2) improve driving performance by reducing driving variability; (3) increase drivers' transient physical activity and body movements while driving; (4) decrease drivers' sense of sleepiness post-drive (but only prior to being challenged with a PVT performance test); and (5) provide the majority of drivers with a sense that the PERCLOS feedback improved their alertness levels. The first three effects (on drowsiness indices, driving performance, and in-cab behaviors) were somewhat more likely to occur during the inbound (return) drive, which consistently involved greater drowsiness than the outbound drive. Moreover, the consistency across these three domains suggests that drivers reduced their drowsiness and driving variability during the PERCLOS feedback condition by becoming more physically active in the cab (e.g., more face, shoulder and neck rubbing; more postural changes; and more total body movements). However, when we examined whether behaviors were more likely to occur during the minutes when PERCLOS indicated drowsiness was present compared to minutes when PERCLOS indicated drowsiness was not present, the descriptive analyses revealed that increased physical activity during driving was not occurring in temporal proximity to PERCLOS indications of drowsiness, but rather the increase in behavioral activity was a function of the feedback condition overall (see Appendix). This finding – namely that the context of feedback was more important than specific PERCLOS contingencies for initiating drivers' compensatory physical activities when driving – was consistent with a number of drivers reporting after the feedback drive that PERCLOS feedback prompted them to "concentrate" more on the driving task and on staying alert. This appeared to be the case for drivers who experienced a greater level of drowsiness during drives, which is precisely the subset of drivers for which a drowsy-driving detection and warning system should be optimized.

The benefits of PERCLOS feedback on driver alertness apparently extended to the post-drive period (i.e., pre-PVT test sleepiness ratings). However, this effect was short-lived. Drivers were no more alert in terms of being able to resist PVT performance lapses after the feedback condition than after the control condition (Figure 25), and they realized this after performing the PVT (i.e., post-PVT sleepiness ratings were not different between feedback and control drives—Figure 24). It is likely that, similar to the sleepiness ratings, the improved alertness while driving in the PERCLOS feedback condition was largely transient and had to be repeatedly rekindled by frequent body movements and extra effort. Subsequent analyses (see Appendix) revealed that these compensatory movements and efforts were probably not initiated only in response to PERCLOS feedback modalities indicating increasing drowsiness (e.g., visual gauge in the red; tonal alarm; voice or peppermint + buzzer alert). The conclusion that the alertness benefits of body movements while driving were likely to have been transient is based on the fact that drivers did not take driving breaks (to attempt to recover), and the kinds of behaviors drivers increased with PERCLOS feedback (e.g., face and neck rubbing) are not known to produce more than a transient effect on alertness—according to a survey of 283 experts in highway safety and sleep research (Nguyen et al., in preparation).

Contrary to our expectations, PERCLOS feedback did not induce drivers to take additional breaks to recover from drowsiness. This outcome may have been influenced by a number of artificial features of the experiment. Notably, drivers were not permitted access to two major countermeasures—napping and caffeine—prompting some of them to avoid taking a break because no viable countermeasure was available. Drivers were also monetarily incented to complete the drive within a time limit, which likely reduced their willingness to stop. Whether or not these factors suppressed drivers' willingness to take breaks, it is important for future studies that might seek to implement automated drowsiness detection systems in trucks, to identify the factors that determine when, where, and how long truck drivers take rest breaks. It also remains to be determined whether an automated PERCLOS feedback system used by over-the-road truckers would prompt drivers to engage in napping and caffeine countermeasures that are documented to reduce drowsiness.

The reliability of the study findings would have been enhanced by inclusion of an additional five drivers to determine whether many of the data trends ($0.10 > p > 0.05$) would reach statistical significance. However, there were no additional drivers available within the time constraints and resources of the project. Nevertheless, the remarkable consistency of PERCLOS feedback effects across drowsiness indices, driving performance metrics, behavioral variables, and drivers' perceptions of benefit, suggests that an automated PERCLOS drowsy-driving system should be transitioned to field studies (over the road) to answer a number of questions regarding its effectiveness and proper use. The deployment of such a system will require more information on driver usage patterns (e.g., when do drivers turn the system on and off?); and driver feedback preferences (e.g., which types of feedback do drivers prefer?). There will also have to be information obtained on ways in which the system may be misused.

It is important to acknowledge that the current study has a number of limitations. Although our original validation study identified PERCLOS as the most promising technology development area for a drowsy-driving monitor (Dinges et al., 1998), the automated PERCLOS system of CMRI used in this study was not validated in a controlled laboratory setting to confirm that it was as accurate in predicting PVT lapses as the video-based, human-scored PERCLOS measure we tested in the original validation study. If this new CMRI automated PERCLOS monitor (or any other automated PERCLOS monitor) is to be used over the road, even in test trials, we believe it should be re-validated in the laboratory for its accuracy in predicting performance hypovigilance (lapses), to ensure that this critical criterion is being met.

It is also noteworthy that the automated PERCLOS tested in the current experiment did not function in ambient daylight and it was not able to discriminate loss of signal (e.g., due to turning the head) from prolonged eyelid closure. It is essential that both of these limitations be overcome before the CMRI automated PERCLOS can be effectively used in field trials.

This study did not involve a test of the individual components of CMRI's automated PERCLOS feedback system, with the exception of comparing the effects of voice alerts with those of peppermint + buzzer alerts. (The latter were not very informative.) Our conclusions, therefore, apply to the entire CMRI automated PERCLOS system, and not to sub-components of the system. In other words, we do not know whether we would have obtained the same results if the feedback condition had involved only a visual feedback gauge with a tonal alarm (but no warning alerts).

Finally, we note that in this experiment drivers drove only two legs (1 nighttime drive) with automated PERCLOS feedback. We do not know how drivers would use this system if it were available night after night. It is possible that some of the beneficial effects we observed were due to the novelty of the feedback condition. Studies should be undertaken to determine whether the beneficial effects of feedback from an automated PERCLOS monitor could be sustained over many nights or weeks of operations.

APPENDIX

Analysis of Timing of Behavioral Responses

The report contains clear evidence that when drivers operated in the PERCLOS feedback condition, relative to the no-feedback condition, they had lower drowsiness indices; better driving performance, and increased behaviors (e.g., more head rubbing; more postural changes; more total body movements). Consequently, feedback promoted a more alert, effortful and safer driver. The question we sought to address in the analyses contained in this Appendix is whether during the PERCLOS feedback condition drivers' behaviors were occurring in response to PERCLOS warnings of drowsiness. That is, the following analyses tested whether drivers' increased body movements during the feedback condition were occurring during the <u>minute</u> in which PERCLOS signaled increasing drowsiness (i.e., behaviors were in close temporal proximity to PERLOS warnings). Alternatively, PERCLOS feedback could have had a generalized activation effect on drivers by prompting them to initiate more behaviors overall, without those behaviors occurring exclusively in response to PERCLOS indications of increasing drowsiness (e.g., some drivers reported that feedback caused them to concentrate more on the driving task). This alternative outcome would suggest that drivers were not relying on PERCLOS to inform them when drowsiness was increasing before engaging in compensatory behaviors and effort.

<u>Descriptive analysis.</u> The objectives of this descriptive analysis were to examine if there were systematic behavioral responses to the PERCLOS 1-minute and/or 3-minute feedback indicators. We aimed to see if behaviors were more likely to be expressed during times when feedback was present compared to times when feedback was not present. That is, we examined whether behaviors were more likely to occur during the minutes when PERCLOS indicated drowsiness was present compared to minutes when PERCLOS indicated drowsiness was not present.

Systematic behavioral responses to feedback were *a priori* defined to be present if there were more behaviors than expected during times when feedback indicators were visible to the subject as yellow or red (during feedback). Systematic behavioral responses under feedback were compared to control responses during times when feedback indicators would have been yellow or red had they been visible.

Expected behavior rates were computed for each subject separately by leg (outbound verses inbound) and experimental condition (feedback verses no feedback). The expected behavior rate was set equal to the ratio A/B, where A was defined as the total number of behaviors occurring during the time when the PERCLOS feedback indicator was green (during feedback conditions) or when it would have been green had it been visible to the subject (during control conditions); and B was defined as the total number of minutes during these time leg and condition specific time intervals. This rate was named the "***Green Behavior Rate.***"

The numbers of expected behaviors were computed for each leg and condition by multiplying the *green behavior rate* by the number of minutes when the PERCLOS feedback indicator was yellow or red (during feedback conditions) or when it would have been yellow or red had it been visible to the subject (during control conditions).

Excess behaviors were defined as the difference between the number of observed behaviors and the number of *expected behaviors*.

Separate analyses were performed under the following feedback conditions:

1. Pooling times when the PERCLOS 1-minute feedback indicator lights were yellow (i.e., when $0.12 \leq$ PERCLOS 1-min. < 0.21) or red (i.e., when PERCLOS 1-min. ≥ 0.21);
2. When the PERCLOS 1 feedback indicator lights were red (i.e., PERCLOS 1-min. $\geq$ 0.21);
3. Pooling times when the PERCLOS 3-minute feedback indicator lights were yellow (i.e., when $0.12 \leq$ PERCLOS 3-min) < 0.21) or red (i.e., when PERCLOS 3-min ≥ 0.21);
4. When the PERCLOS 3-min.feedback indicator lights were red (i.e., PERCLOS 3-min. $\geq$ 0.21);

Separate analyses were performed for total behaviors and for a <u>subset of 4 behaviors</u> found to be sensitive with regard to experimental conditions. This subset included neck and shoulder rubs, postural changes, rubbing face, and stretching.

We compared the rates and numbers of 'excess behaviors' between the feedback and control conditions. Thus, the focus was on whether there was greater clustering of behaviors during feedback compared to times when feedback was not present (control condition). The primary comparison was defined to be the comparison of total behaviors comparing times when the PERCLOS 1-minute feedback indicator lights were yellow (i.e., when $0.12 \leq$ PERCLOS 1-min. $<$ 0.21) or red (i.e., when PERCLOS 1-min. ≥ 0.21) to when they were green.

<u>Timing of Behaviors in Response to PERCLOS Feedback.</u>

Table 7 through Table 14 present subject-specific data for total behaviors (Tables 7 – 10 show the results for 1-minute PERCLOS, and Tables 11 – 14 show the results for 3-minute PERCLOS). Table 7 lists the numbers of minutes and behaviors per minute when the indicator was green (or would have been green if visible under the control no-feedback condition). Table 8 displays the numbers of observed behaviors when the indicator was either yellow or red (or would have been yellow or red if visible under the control condition) based one the 1-minute PERCLOS indicator. Table 8 also lists the expected numbers of behaviors under the (null) hypothesis that the behavior rates were the same for 'yellow and red minutes' as they were for 'green' minutes. Finally, Table 8 also lists observed minus expected differences. Tables 7 and 8 constitute the *a priori* defined primary analysis. **Large positive differences would indicate that behaviors tended to be clustered around 'feedback minutes'. If this were so, we would expect large positive differences under the *feedback* condition but not under the *control* condition.** Tables 9 and 10 provide the analogous information for comparing 'red' minutes to 'green' minutes, also based on the 1-minute PERCLOS indicator. Tables 11 and 12 and Tables 13 and 14 provide the analogous analyses based on the <u>3-minute PERCLOS</u> indicator. Results for 'red' minutes were limited due to the limited incidence of red minutes in our samples. Table 15 through Table 22 display the same type of results as Tables 7 through 14, but do so only for the subset of behaviors that were found to be most affected by PERCLOS feedback (i.e., neck and shoulder rubs, postural changes, rubbing face, and stretching).

As is evident in all of these Tables, there were substantial inter-individual differences. In some cases, there were very few minutes in which PERCLOS 1 or PERCLOS 3 were larger than 0.12 (e.g., see Figures 26, 27, 29, 30, 32, 38, 41, 48, 52, 53, 56 and 57). In other cases, such as subject 3006, there were very few minutes where PERCLOS was smaller than 0.12 (see Figures 33 and 49; for examples of other subjects with frequently high PERCLOS values, see Figures 28, 44, 47, 51, 55). In both situations, the estimated expected numbers of behaviors are likely to be unstable. Therefore, non-parametric summary statistics (median, 25th percentile and 75th percentile) were used in the descriptive analyses.

In Table 7, we see that the number of median values of 'yellow + red' minutes were very similar under both the feedback and control conditions during the outbound legs. In contrast, the median value was more than twice as large in the inbound control condition compared to the inbound feedback condition (13.0 vs. 5.0). As we might expect, the 'Green Behavior rates' were larger during the inbound legs compared to the outbound legs under both the feedback condition (0.665 vs. 0.464 events/minute) and the control condition (0.509 vs. 0.315 events/minute). Interestingly, the Green Behavior rates were larger under the feedback condition during both the outbound leg (0.464 vs. 0.315 behaviors/minute) and the inbound leg (0.665 vs. 0.509), suggesting the possibility of a generalized activation during the feedback condition. The critical question was whether these behaviors tended to be clustered during time when feedback was available. The aim of Table 8 was to examine this issue. However, as noted above general conclusions were somewhat limited by the small numbers of feedback minutes among some subjects for some legs. Therefore, our analyses focused on examining patterns of behaviors for specific subjects.

Subject 3007. This subject appeared to have sufficient non-feedback and feedback minutes to examine whether behaviors tended to cluster concomitantly with feedback (see also Figures 34 and 50). As shown in Table 7, the 'Green Behavior' rates for PERCLOS 1 minute were 0.610, 0.283, 1.101, and 0.935, respectively for the outbound/feedback, outbound/control, inbound/feedback, and inbound/control conditions. The numbers of feedback minutes were 9, 12, 21, and 44 minutes, respectively for the outbound/feedback, outbound/control, inbound/feedback, and inbound/control conditions. Based on the Green Behavior rates, we would, therefore, expect 5.5, 3.4, 23.1, and 41.2 total behaviors, respectively, during these intervals (see Table 8). In fact, we observed 5, 2, 18, and 53 behaviors, respectively (Table 8). Thus, for PERCLOS 1-minute feedback, the observed minus expected differences were –0.5, -1.4, -5.1, and 11.8, respectively. Interestingly, there were fewer behaviors than expected during the inbound feedback condition and more behaviors than expected during the inbound control condition. Thus, it appears that total behaviors were <u>not</u> clustered concomitantly for this subject.

Tables 15 and 16 provide the analogous comparisons for subject 3007 for the combination of all four subset behaviors observed to change with PERCLOS feedback (i.e., neck and shoulder rubs, postural changes, rubbing face, and stretching). The observed minus expected differences for subject 3007 for the outbound/feedback, outbound/control, inbound/feedback, and inbound/control conditions were +0.5, -1.0, -1.0, +9.4, respectively. Thus, restricting attention to the subset behaviors did not change the substantive results. Subject 3007 had only 1 'red' feedback minute preventing meaningful analyses. When PERCLOS 3 was examined (Tables 11 and 12) for this subject, the observed minus expected differences for the outbound/feedback, outbound/control, inbound/feedback, and inbound/control conditions were –0.8, 1.7, -4.7, and 27.6, respectively. Thus, the observed and expected differences for subject 3007 were even more contradictory for the subset behaviors, in support of the 'clustering hypothesis.'

<u>Subject 3008</u>. Subject 3008 also had substantial numbers of minutes during 'feedback' and 'non-feedback' times (se Tables 7 and 15, and Figures 35 and 51). This subject had the largest Green Behavior rates under three of the four experimental conditions. The number of 'feedback' minutes was substantially larger under the control conditions compared to the feedback conditions (outbound 50 verses 9, inbound 71 versus 21). 'Excess' total behaviors were negative for both feedback legs (outbound = –0.2 and inbound = - 4.4). There were no 1-minute PERCLOS 'red' minutes (Tables 9 and 10). Excess total behaviors were also negative for 3-minute PERCLOS (Tables 11 and 12).

<u>Subject 3006.</u> The subject with the largest number of 'excess' behaviors was subject 3006 (see Figures 33 and 49). During the inbound feedback leg, excess behaviors were estimated to be equal to 27. This is because there were only 7 minutes of 'green' time during this leg and no behaviors were exhibited. Thus, the expected number of behaviors was 0 and so all were attributed to being 'in excess.' In contrast, during the outbound feedback leg, 'excess' behaviors were negative.

<u>Other Subjects.</u> For the 1-minute PERCLOS conditions defining feedback as yellow or red indicator lights, all of the outbound feedback estimates of 'excess' behaviors were negative. In contrast, some of the differences between observed and expected behaviors during control outbound legs were positive and some were negative. There did not appear to be consistent patterns during the inbound legs. Similar results were observed for 3-minute PERCLOS.

<u>Graphical Analyses.</u> In addition to descriptive analyses of the relationship between

PERCLOS feedback and driver behaviors, graphical comparisons were made for each individual driver of the temporal relationships between PERCLOS 1-minute feedback and the subset of behaviors increased by PERCLOS feedback (i.e., neck and shoulder rubs, postural changes, rubbing face, and stretching). The 32 graphical comparisons for the PERCLOS FEEDBACK condition are displayed in Figure 26 through Figure 41 for the outbound drive leg, and in Figure 42 through Figure 57 for the inbound drive leg. Examination of these figures tends to substantiate (1) the large inter-individual differences in PERCLOS values (e.g., compare subject 2002, Figure 27 to subject 2005, Figure 28); and (2) the increased PERCLOS values for the inbound drive leg relative to the outbound drive leg (e.g., compare Subject 2002 Figure 27 and Figure 43). However, examination of Figures 26 through 57 does not find much support for the hypothesis that behavior was changing in close temporal proximity to PERCLOS feedback that drowsiness was present. Rather, the subset behaviors tended to occur overall more often when PERCLOS feedback was present (see Figures 29, 21, 22), but not necessarily in the same minute that PERCLOS indicated increasing drowsiness.

Appendix Discussion and Conclusions

The descriptive analyses of the timing of behaviors in response to PERCLOS feedback appeared to confirm overall behavioral responses to the feedback condition as evidenced by the larger median behavior rates per minute during the feedback conditions compared to the no-feedback (control) conditions (Table 7). However, our analyses of the timing of events within the PERCLOS feedback condition (driver behaviors relative to the changes in PERCLOS-1 and PERCLOS-3 indicator lights) revealed no evidence that drivers' behaviors tended to cluster concomitantly with PERCLOS feedback signals. Detailed graphical analyses for each individual subject (during both outbound and inbound drive legs) of the temporal relationships between PERCLOS 1-minute feedback and the subset of behaviors increased by PERCLOS feedback, also failed to support a tight temporal relationship between PERCLOS signals of drowsiness and overt behavioral responses (see Figure 26 through Figure 57).

Thus, the descriptive and graphical analyses revealed that increased physical activity during driving was <u>not</u> occurring in temporal proximity to PERCLOS indications of drowsiness, but rather the increase in behavioral activity was a function of the feedback condition overall. This finding – namely that the context of feedback was more important than specific PERCLOS contingencies for initiating drivers' compensatory physical activities when driving – was consistent with a number of drivers reporting after the feedback drive that PERCLOS feedback prompted them to "concentrate" more on the driving task and on staying alert. This appeared to be the case for drivers who experienced a greater level of drowsiness during drives, which is precisely the subset of drivers for which a drowsy-driving detection and warning system should be optimized.

Table 7
1 Minute PERCLOS
Numbers of Minutes and Total Behaviors per Minute When Indicator Was Green and the Number of Minutes Indicator was Either Yellow or Red

	Green Minutes				Green Behavior Rate				Yellow+Red Minutes			
	Outbound		Inbound		Outbound		Inbound		Outbound		Inbound	
Subject	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control
2001	78	92	120	93	0.321	0.217	0.492	0.344	1	1	0	0
2002	104	93	86	86	0.269	0.839	0.500	0.523	0	2	6	13
2005	68	93	63	94	0.809	0.387	1.317	0.734	24	0	27	0
3001	96	91	95	91	0.490	0.440	0.432	0.451	0	0	4	0
3003	101	87	104	52	0.129	0.253	0.394	0.731	0	9	3	47
3004	85	97	65	94	0.424	0.464	0.615	0.723	13	1	29	2
3005	92	95	91	95	0.609	0.179	0.670	0.495	1	0	0	1
3006	6	19	1	7	0.333	0.263	0.000	0.429	83	71	90	80
3007	100	92	89	62	0.610	0.283	1.101	0.935	9	12	21	44
3008	83	42	70	18	1.241	1.214	0.829	1.389	9	50	21	71
3009	90	91	92	86	0.211	0.209	0.207	0.244	5	1	0	5
3010	92	41	93	18	0.902	0.585	1.366	0.556	3	57	0	78
3011	93	94	88	86	0.903	0.670	1.625	0.895	0	0	6	4
3012	87	50	88	10	0.437	0.240	0.659	0.200	7	46	9	82
3013	79	88	92	71	0.418	0.284	0.467	0.394	13	5	0	28
3014	96	81	96	87	0.771	0.346	0.938	0.322	0	17	0	13
Median	**91**	**91**	**90**	**86**	**0.464**	**0.315**	**0.637**	**0.509**	**4.0**	**3.5**	**5.0**	**13.0**
25%	82	73.25	82	43.5	0.330	0.250	0.458	0.382	0.0	0.8	0.0	1.8
50%	96	93	93.5	91.5	0.781	0.494	0.979	0.732	10.0	24.3	21.0	53.0

Notes: 'Green Minutes' are defined as minutes when PERCLOS 1 was less than 0.12. Under the Feedback Condition, a top row green indicator was visible to the subject. 'Yellow+Red Minutes' are defined as minutes when PERCLOS 1 was greater than or equal to 0.12. Under the Feedback Condition, a top row yellow or red indicator was visible to the subject.

Table 8
1 Minute PERCLOS
Numbers of Observed and Expected Total Behaviors
When the Indicator was Either Yellow or Red

	P1: Yellow+Red Observed Behaviors				P1: Yellow+Red Expected Behaviors				P1: Yellow+Red Obs. - Exp. Behaviors.			
	Outbound		Inbound		Outbound		Inbound		Outbound		Inbound	
Subject	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control
2001	0	0			0.3	0.2			-0.3	-0.2		
2002		2	3	8		1.7	3.0	6.8		0.3	0.0	1.2
2005	10		36		19.4		35.6		-9.4		0.4	
3001			0				1.7				-1.7	
3003		6	4	50		2.3	1.2	34.3		3.7	2.8	15.7
3004	3	0	11	1	5.5	0.5	17.8	1.4	-2.5	-0.5	-6.8	-0.4
3005	0			0	0.6			0.5	-0.6			-0.5
3006	22	23	27	33	27.7	18.7	0.0	34.3	-5.7	4.3	27.0	-1.3
3007	5	2	18	53	5.5	3.4	23.1	41.2	-0.5	-1.4	-5.1	11.8
3008	11	55	13	73	11.2	60.7	17.4	98.6	-0.2	-5.7	-4.4	-25.6
3009	0	0		1	1.1	0.2		1.2	-1.1	-0.2		-0.2
3010	1	44		66	2.7	33.4		43.3	-1.7	10.6		22.7
3011			17	5			9.8	3.6			7.3	1.4
3012	1	11	6	56	3.1	11.0	5.9	16.4	-2.1	0.0	0.1	39.6
3013	4	2		9	5.4	1.4		11.0	-1.4	0.6		-2.0
3014		4		6		5.9		4.2		-1.9		1.8
Median	**3**	**3**	**12**	**9**	**5.4**	**2.8**	**7.8**	**11.0**	**-1.4**	**-0.1**	**0.0**	**1.2**
25%	0.5	1.5	4.5	5	1.9	1.2	2.0	3.6	-2.3	-0.7	-3.7	-0.5
50%	7.5	14	17.75	53	8.3	13.0	17.7	34.3	-0.5	1.4	2.2	11.8

Notes: 'Green Minutes' are defined as minutes when PERCLOS 1 was less than 0.12. Under the Feedback Condition, a top row green indicator was visible to the subject. 'Yellow+Red Minutes' are defined as minutes when PERCLOS 1 was greater than or equal to 0.12. Under the Feedback Condition, a top row yellow or red indicator was visible to the subject.

Table 9

1 Minute PERCLOS
Numbers of Minutes and Total Behaviors per Minute When Indicator Was Green and the Number of Minutes Indicator was Red

	Green Minutes				Green Behavior Rate				Red Minutes			
	Outbound		Inbound		Outbound		Inbound		Outbound		Inbound	
Subject	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control
2001	78	92	120	93	0.321	0.217	0.492	0.344	0	0	0	0
2002	104	93	86	86	0.269	0.839	0.500	0.523	0	0	0	1
2005	68	93	63	94	0.809	0.387	1.317	0.734	2	0	3	0
3001	96	91	95	91	0.490	0.440	0.432	0.451	0	0	0	0
3003	101	87	104	52	0.129	0.253	0.394	0.731	0	1	0	18
3004	85	97	65	94	0.424	0.464	0.615	0.723	0	0	3	0
3005	92	95	91	95	0.609	0.179	0.670	0.495	0	0	0	0
3006	6	19	1	7	0.333	0.263	0.000	0.429	52	22	84	51
3007	100	92	89	62	0.610	0.283	1.101	0.935	1	0	0	13
3008	83	42	70	18	1.241	1.214	0.829	1.389	0	20	0	39
3009	90	91	92	86	0.211	0.209	0.207	0.244	1	0	0	0
3010	92	41	93	18	0.902	0.585	1.366	0.556	0	7	0	24
3011	93	94	88	86	0.903	0.670	1.625	0.895	0	0	0	0
3012	87	50	88	10	0.437	0.240	0.659	0.200	0	7	0	28
3013	79	88	92	71	0.418	0.284	0.467	0.394	0	0	0	4
3014	96	81	96	87	0.771	0.346	0.938	0.322	0	0	0	3
Median	**91**	**91**	**90**	**86**	**0.464**	**0.315**	**0.637**	**0.509**	**0.0**	**0.0**	**0.0**	**2.0**
25%	82	73.25	82	43.5	0.330	0.250	0.458	0.382	0.0	0.0	0.0	0.0
50%	96	93	93.5	91.5	0.781	0.494	0.979	0.732	0.3	2.5	0.0	19.5

Notes: 'Green Minutes' are defined as minutes when PERCLOS 1 was less than 0.12. Under the Feedback Condition, a top row green indicator was visible to the subject. 'Red Minutes' are defined as minutes when PERCLOS 1 was greater than or equal to 0.21. Under the Feedback Condition, a top row red indicator was visible to the subject.

Table 10
1 Minute PERCLOS
Numbers of Observed and Expected Total Behaviors
When the Indicator was Red

	P1: Red Observed Behaviors				P1: Red Expected Behaviors				P1: Red Obs. - Exp. Behaviors.			
	Outbound		Inbound		Outbound		Inbound		Outbound		Inbound	
Subject	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control
2001												
2002				0				0.5				-0.5
2005	0		5		1.6		4.0		-1.6		1.0	
3001												
3003		1		19		0.3		13.2		0.7		5.8
3004			0				1.8				-1.8	
3005												
3006	14	10	26	26	17.3	5.8	0.0	21.9	-3.3	4.2	26.0	4.1
3007	0			9	0.6			12.2	-0.6			-3.2
3008		17		35		24.3		54.2		-7.3		-19.2
3009	0				0.2				-0.2			
3010		6		22		4.1		13.3		1.9		8.7
3011												
3012		2		19		1.7		5.6		0.3		13.4
3013				1				1.6				-0.6
3014				1				1.0				0.0
Median	**0**	**6**	**5**	**19**	**1.1**	**4.1**	**1.8**	**12.2**	**-1.1**	**0.7**	**1.0**	**0.0**
25%	0	2	2.5	1	0.5	1.7	0.9	1.6	-2.0	0.3	-0.4	-0.6
50%	3.5	10	15.5	22	5.5	5.8	2.9	13.3	-0.5	1.9	13.5	5.8

Notes: 'Green Minutes' are defined as minutes when PERCLOS 1 was less than 0.12. Under the Feedback Condition, a top row green indicator was visible to the subject. 'Red Minutes' are defined as minutes when PERCLOS 1 was greater than or equal to 0.21. Under the Feedback Condition, a top row red indicator was visible to the subject.

Table 11
3 Minute PERCLOS
Numbers of Minutes and Total Behaviors per Minute When Indicator Was Green and the Number of Minutes Indicator was Either Red or Yellow

	Green Minutes				Green Behavior Rate				Yellow+Red Minutes			
	Outbound		Inbound		Outbound		Inbound		Outbound		Inbound	
Subject	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control
2001	79	93	120	93	0.316	0.215	0.492	0.344	0	0	0	0
2002	104	94	91	92	0.269	0.851	0.505	0.554	0	1	1	7
2005	67	93	63	94	0.806	0.387	1.349	0.734	25	0	27	0
3001	96	91	99	91	0.490	0.440	0.414	0.451	0	0	0	0
3003	101	87	107	48	0.129	0.276	0.421	0.708	0	9	0	51
3004	93	98	72	96	0.409	0.459	0.583	0.719	5	0	22	0
3005	93	95	91	96	0.602	0.179	0.670	0.490	0	0	0	0
3006	4	11	2	2	0.000	0.364	0.000	0.000	85	79	89	85
3007	106	103	92	61	0.613	0.252	1.098	0.787	3	1	18	45
3008	90	37	80	20	1.244	1.297	0.813	1.450	2	55	11	69
3009	93	92	92	91	0.204	0.207	0.207	0.242	2	0	0	0
3010	95	33	93	23	0.884	0.576	1.366	0.957	0	65	0	73
3011	93	94	94	90	0.903	0.670	1.702	0.911	0	0	0	0
3012	91	50	97	4	0.418	0.180	0.660	0.250	3	46	0	88
3013	89	93	92	71	0.404	0.290	0.467	0.423	3	0	0	28
3014	96	88	96	94	0.771	0.341	0.938	0.340	0	10	0	6
Median	**93**	**92.5**	**92**	**90.5**	**0.454**	**0.353**	**0.622**	**0.522**	**1.0**	**0.5**	**0.0**	**6.5**
25%	89.75	77.75	88.25	41.75	0.304	0.243	0.456	0.343	0.0	0.0	0.0	0.0
50%	96	94	96.25	93.25	0.780	0.488	0.978	0.747	3.0	19.0	12.8	55.5

Notes: 'Green Minutes' are defined as minutes when PERCLOS 3 was less than 0.12. Under the Feedback Condition, a bottom row green indicator was visible to the subject. 'Yellow+Red Minutes' are defined as minutes when PERCLOS 3 was greater than or equal to 0.21. Under the Feedback Condition, a bottom row red indicator was visible to the subject.

Table 12
3 Minute PERCLOS
Numbers of Observed and Expected Total Behaviors
When the Indicator was Yellow or Red

	P3: Yellow+Red Observed Behaviors				P3: Yellow+Red Expected Behaviors				P3: Yellow+Red Obs. - Exp. Behaviors.			
	Outbound		Inbound		Outbound		Inbound		Outbound		Inbound	
Subject	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control
2001												
2002		0	0	2		0.9	0.5	3.9		-0.9	-0.5	-1.9
2005	11		34		20.1		36.4		-9.1		-2.4	
3001												
3003		4		54		2.5		36.1		1.5		17.9
3004	1		9		2.0		12.8		-1.0		-3.8	
3005												
3006	24	24	27	36	0.0	28.7	0.0	0.0	24.0	-4.7	27.0	36.0
3007	1	2	15	63	1.8	0.3	19.8	35.4	-0.8	1.7	-4.8	27.6
3008	2	58	6	69	2.5	71.4	8.9	100.1	-0.5	-13.4	-2.9	-31.1
3009	0				0.4				-0.4			
3010		49		54		37.4		69.8		11.6		-15.8
3011												
3012	1	14		57	1.3	8.3		22.0	-0.3	5.7		35.0
3013	1			7	1.2			11.8	-0.2			-4.8
3014		2		2		3.4		2.0		-1.4		0.0
Median	**1**	**9**	**12**	**54**	**1.5**	**5.8**	**10.9**	**22.0**	**-0.4**	**0.3**	**-2.7**	**0.0**
25%	1	2	6.75	7	1.0	2.1	2.6	3.9	-0.9	-2.2	-3.6	-4.8
50%	4.25	30.25	24	57	2.2	30.9	18.0	36.1	-0.2	2.7	-1.0	27.6

Notes: 'Green Minutes' are defined as minutes when PERCLOS 3 was less than 0.12. Under the Feedback Condition, a bottom row green indicator was visible to the subject. 'Yellow+Red Minutes' are defined as minutes when PERCLOS 3 was greater than or equal to 0.21. Under the Feedback Condition, a bottom row red indicator was visible to the subject.

Table 13
3 Minute PERCLOS
Numbers of Minutes and Total Behaviors per Minute When Indicator Was Green and the Number of Minutes Indicator was Red

	Green Minutes				Green Behavior Rate				Red Minutes			
	Outbound		Inbound		Outbound		Inbound		Outbound		Inbound	
Subject	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control
2001	79	93	120	93	0.316	0.215	0.492	0.344	0	0	0	0
2002	104	94	91	92	0.269	0.851	0.505	0.554	0	0	0	0
2005	67	93	63	94	0.806	0.387	1.349	0.734	1	0	3	0
3001	96	91	99	91	0.490	0.440	0.414	0.451	0	0	0	0
3003	101	87	107	48	0.129	0.276	0.421	0.708	0	0	0	20
3004	93	98	72	96	0.409	0.459	0.583	0.719	0	0	0	0
3005	93	95	91	96	0.602	0.179	0.670	0.490	0	0	0	0
3006	4	11	2	2	0.000	0.364	0.000	0.000	53	20	84	49
3007	106	103	92	61	0.613	0.252	1.098	0.787	0	0	0	9
3008	90	37	80	20	1.244	1.297	0.813	1.450	0	17	0	40
3009	93	92	92	91	0.204	0.207	0.207	0.242	0	0	0	0
3010	95	33	93	23	0.884	0.576	1.366	0.957	0	2	0	28
3011	93	94	94	90	0.903	0.670	1.702	0.911	0	0	0	0
3012	91	50	97	4	0.418	0.180	0.660	0.250	0	1	0	20
3013	89	93	92	71	0.404	0.290	0.467	0.423	0	0	0	0
3014	96	88	96	94	0.771	0.341	0.938	0.340	0	0	0	0
Median	**93**	**92.5**	**92**	**90.5**	**0.454**	**0.353**	**0.622**	**0.522**	**0.0**	**0.0**	**0.0**	**0.0**
25%	89.75	77.75	88.25	41.75	0.304	0.243	0.456	0.343	0.0	0.0	0.0	0.0
50%	96	94	96.25	93.25	0.780	0.488	0.978	0.747	0.0	0.3	0.0	20.0

Notes: 'Green Minutes' are defined as minutes when PERCLOS 3 was less than 0.12. Under the Feedback Condition, a bottom row green indicator was visible to the subject. 'Red Minutes' are defined as minutes when PERCLOS 3 was greater than or equal to 0.21. Under the Feedback Condition, a bottom row red indicator was visible to the subject.

Table 14

3 Minute PERCLOS
Numbers of Observed and Expected Total Behaviors
When the Indicator was Red

	P3: Red Observed Behaviors				P3: Red Expected Behaviors				P3: Red Obs. - Exp. Behaviors.			
	Outbound		Inbound		Outbound		Inbound		Outbound		Inbound	
Subject	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control
2001												
2002												
2005	0		6		0.8		4.0		-0.8		2.0	
3001												
3003				22				14.2				7.8
3004												
3005												
3006	14	6	26	24	0.0	7.3	0.0	0.0	14.0	-1.3	26.0	24.0
3007				10				7.1				2.9
3008		13		37		22.1		58.0		-9.1		-21.0
3009												
3010		1		20		1.2		26.8		-0.2		-6.8
3011												
3012		1		13		0.2		5.0		0.8		8.0
3013												
3014												
Median	**7**	**3.5**	**16**	**21**	**0.4**	**4.2**	**2.0**	**10.6**	**6.6**	**-0.7**	**14.0**	**5.4**
25%	3.5	1	11	14.75	0.2	0.9	1.0	5.5	2.9	-3.2	8.0	-4.4
50%	10.5	7.75	21	23.5	0.6	11.0	3.0	23.6	10.3	0.1	20.0	8.0

Notes: 'Green Minutes' are defined as minutes when PERCLOS 3 was less than 0.12. Under the Feedback Condition, a bottom row green indicator was visible to the subject. 'Red Minutes' are defined as minutes when PERCLOS 3 was greater than or equal to 0.21. Under the Feedback Condition, a bottom row red indicator was visible to the subject.

Table 15
1 Minute PERCLOS
Numbers of Minutes and Subset Behaviors per Minute When Indicator Was Green and the Number of Minutes Indicator was Either Yellow or Red

	Green Minutes				Green Behavior Rate				Yellow+Red Minutes			
	Outbound		Inbound		Outbound		Inbound		Outbound		Inbound	
Subject	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control
2001	78	92	120	93	0.026	0.087	0.208	0.075	1	1	0	0
2002	104	93	86	86	0.135	0.527	0.326	0.291	0	2	6	13
2005	68	93	63	94	0.088	0.097	0.492	0.053	24	0	27	0
3001	96	91	95	91	0.146	0.187	0.137	0.132	0	0	4	0
3003	101	87	104	52	0.059	0.057	0.096	0.135	0	9	3	47
3004	85	97	65	94	0.259	0.113	0.185	0.245	13	1	29	2
3005	92	95	91	95	0.098	0.116	0.264	0.263	1	0	0	1
3006	6	19	1	7	0.000	0.053	0.000	0.000	83	71	90	80
3007	100	92	89	62	0.280	0.087	0.573	0.242	9	12	21	44
3008	83	42	70	18	0.398	0.286	0.371	0.556	9	50	21	71
3009	90	91	92	86	0.067	0.099	0.087	0.151	5	1	0	5
3010	92	41	93	18	0.478	0.220	0.398	0.278	3	57	0	78
3011	93	94	88	86	0.398	0.309	0.682	0.384	0	0	6	4
3012	87	50	88	10	0.172	0.080	0.330	0.000	7	46	9	82
3013	79	88	92	71	0.051	0.034	0.054	0.042	13	5	0	28
3014	96	81	96	87	0.375	0.123	0.531	0.092	0	17	0	13
Median	**91**	**91**	**90**	**86**	**0.141**	**0.106**	**0.295**	**0.143**	**4.0**	**3.5**	**5.0**	**13.0**
25%	82	73.25	82	43.5	0.065	0.085	0.127	0.070	0.0	0.8	0.0	1.8
50%	96	93	93.5	91.5	0.304	0.195	0.422	0.267	10.0	24.3	21.0	53.0

Notes: 'Green Minutes' are defined as minutes when PERCLOS 1 was less than 0.12. Under the Feedback Condition, a top row green indicator was visible to the subject. 'Yellow+Red Minutes' are defined as minutes when PERCLOS 1 was greater than or equal to 0.12. Under the Feedback Condition, a top row yellow or red indicator was visible to the subject.

Table 16
1 Minute PERCLOS
Numbers of Observed and Expected Subset Behaviors
When the Indicator was Either Yellow or Red

	P1: Yellow+Red Observed Behaviors				P1: Yellow+Red Expected Behaviors				P1: Yellow+Red Obs. - Exp. Behaviors.			
	Outbound		Inbound		Outbound		Inbound		Outbound		Inbound	
Subject	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control
2001	0	0			0.0	0.1			0.0	-0.1		
2002		2	2	4		1.1	2.0	3.8		0.9	0.0	0.2
2005	2		17		2.1		13.3		-0.1		3.7	
3001			0				0.5				-0.5	
3003		0	0	5		0.5	0.3	6.3		-0.5	-0.3	-1.3
3004	2	0	1	0	3.4	0.1	5.4	0.5	-1.4	-0.1	-4.4	-0.5
3005	0			0	0.1			0.3	-0.1			-0.3
3006	6	2	5	6	0.0	3.7	0.0	0.0	6.0	-1.7	5.0	6.0
3007	3	0	11	20	2.5	1.0	12.0	10.6	0.5	-1.0	-1.0	9.4
3008	2	13	7	16	3.6	14.3	7.8	39.4	-1.6	-1.3	-0.8	-23.4
3009	0	0		1	0.3	0.1		0.8	-0.3	-0.1		0.2
3010	1	17		23	1.4	12.5		21.7	-0.4	4.5		1.3
3011			7	2			4.1	1.5			2.9	0.5
3012	1	5	6	28	1.2	3.7	3.0	0.0	-0.2	1.3	3.0	28.0
3013	1	0		2	0.7	0.2		1.2	0.3	-0.2		0.8
3014		1		3		2.1		1.2		-1.1		1.8
Median	**1**	**0.5**	**5.5**	**4**	**1.2**	**1.0**	**3.5**	**1.2**	**-0.1**	**-0.1**	**-0.1**	**0.5**
25%	0.5	0	1.25	2	0.2	0.2	0.9	0.5	-0.4	-1.1	-0.7	-0.3
50%	2	2.75	7	16	2.3	3.7	7.2	6.3	0.2	0.2	3.0	1.8

Notes: 'Green Minutes' are defined as minutes when PERCLOS 1 was less than 0.12. Under the Feedback Condition, a top row green indicator was visible to the subject. 'Yellow+Red Minutes' are defined as minutes when PERCLOS 1 was greater than or equal to 0.12. Under the Feedback Condition, a top row yellow or red indicator was visible to the subject.

Table 17
1 Minute PERCLOS
Numbers of Minutes and Subset Behaviors per Minute When Indicator Was Green and the Number of Minutes Indicator was Red

	Green Minutes				Green Behavior Rate				Red Minutes			
	Outbound		Inbound		Outbound		Inbound		Outbound		Inbound	
Subject	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control
2001	78	92	120	93	0.026	0.087	0.208	0.075	0	0	0	0
2002	104	93	86	86	0.135	0.527	0.326	0.291	0	0	0	1
2005	68	93	63	94	0.088	0.097	0.492	0.053	2	0	3	0
3001	96	91	95	91	0.146	0.187	0.137	0.132	0	0	0	0
3003	101	87	104	52	0.059	0.057	0.096	0.135	0	1	0	18
3004	85	97	65	94	0.259	0.113	0.185	0.245	0	0	3	0
3005	92	95	91	95	0.098	0.116	0.264	0.263	0	0	0	0
3006	6	19	1	7	0.000	0.053	0.000	0.000	52	22	84	51
3007	100	92	89	62	0.280	0.087	0.573	0.242	1	0	0	13
3008	83	42	70	18	0.398	0.286	0.371	0.556	0	20	0	39
3009	90	91	92	86	0.067	0.099	0.087	0.151	1	0	0	0
3010	92	41	93	18	0.478	0.220	0.398	0.278	0	7	0	24
3011	93	94	88	86	0.398	0.309	0.682	0.384	0	0	0	0
3012	87	50	88	10	0.172	0.080	0.330	0.000	0	7	0	28
3013	79	88	92	71	0.051	0.034	0.054	0.042	0	0	0	4
3014	96	81	96	87	0.375	0.123	0.531	0.092	0	0	0	3
Median	**91**	**91**	**90**	**86**	**0.141**	**0.106**	**0.295**	**0.143**	**0.0**	**0.0**	**0.0**	**2.0**
25%	82	73.25	82	43.5	0.065	0.085	0.127	0.070	0.0	0.0	0.0	0.0
50%	96	93	93.5	91.5	0.304	0.195	0.422	0.267	0.3	2.5	0.0	19.5

Notes: 'Green Minutes' are defined as minutes when PERCLOS 1 was less than 0.12. Under the Feedback Condition, a top row green indicator was visible to the subject. 'Red Minutes' are defined as minutes when PERCLOS 1 was greater than or equal to 0.21. Under the Feedback Condition, a top row red indicator was visible to the subject.

Table 18
1 Minute PERCLOS
Numbers of Observed and Expected Subset Behaviors When the Indicator was Red

	P1: Red Observed Behaviors				P1: Red Expected Behaviors				P1: Red Obs. - Exp. Behaviors.			
	Outbound		Inbound		Outbound		Inbound		Outbound		Inbound	
Subject	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control
2001												
2002				0				0.3				-0.3
2005	0		3		0.2		1.5		-0.2		1.5	
3001												
3003		0		1		0.1		2.4		-0.1		-1.4
3004			0				0.6				-0.6	
3005												
3006	2	0	5	6	0.0	1.2	0.0	0.0	2.0	-1.2	5.0	6.0
3007	0			5	0.3			3.1	-0.3			1.9
3008		3		7		5.7		21.7		-2.7		-14.7
3009	0				0.1				-0.1			
3010		0		8		1.5		6.7		-1.5		1.3
3011												
3012		2		8		0.6		0.0		1.4		8.0
3013				0				0.2				-0.2
3014				1				0.3				0.7
Median	**0**	**0**	**3**	**5**	**0.1**	**1.2**	**0.6**	**0.3**	**-0.1**	**-1.2**	**1.5**	**0.7**
25%	0	0	1.5	1	0.1	0.6	0.3	0.2	-0.2	-1.5	0.5	-0.3
50%	0.5	2	4	7	0.2	1.5	1.0	3.1	0.4	-0.1	3.3	1.9

Notes: 'Green Minutes' are defined as minutes when PERCLOS 1 was less than 0.12. Under the Feedback Condition, a top row green indicator was visible to the subject. 'Red Minutes' are defined as minutes when PERCLOS 1 was greater than or equal to 0.12. Under the Feedback Condition, a top row red indicator was visible to the subject.

Table 19
3 Minute PERCLOS
Numbers of Minutes and Behaviors per Minute When Indicator Was Green and the Number of Minutes Indicator was Either Yellow or Red

	Green Minutes				Green Behavior Rate				Yellow+Red Minutes			
	Outbound		Inbound		Outbound		Inbound		Outbound		Inbound	
Subject	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control
2001	79	93	120	93	0.025	0.086	0.208	0.075	0	0	0	0
2002	104	94	91	92	0.135	0.543	0.330	0.304	0	1	1	7
2005	67	93	63	94	0.090	0.097	0.508	0.053	25	0	27	0
3001	96	91	99	91	0.146	0.187	0.131	0.132	0	0	0	0
3003	101	87	107	48	0.059	0.057	0.093	0.104	0	9	0	51
3004	93	98	72	96	0.258	0.112	0.125	0.240	5	0	22	0
3005	93	95	91	96	0.097	0.116	0.264	0.260	0	0	0	0
3006	4	11	2	2	0.000	0.000	0.000	0.000	85	79	89	85
3007	106	103	92	61	0.283	0.078	0.554	0.197	3	1	18	45
3008	90	37	80	20	0.378	0.297	0.363	0.650	2	55	11	69
3009	93	92	92	91	0.065	0.098	0.087	0.154	2	0	0	0
3010	95	33	93	23	0.474	0.212	0.398	0.348	0	65	0	73
3011	93	94	94	90	0.398	0.309	0.713	0.389	0	0	0	0
3012	91	50	97	4	0.176	0.060	0.361	0.000	3	46	0	88
3013	89	93	92	71	0.056	0.032	0.054	0.042	3	0	0	28
3014	96	88	96	94	0.375	0.102	0.531	0.096	0	10	0	6
Median	**93**	**92.5**	**92**	**90.5**	**0.141**	**0.100**	**0.297**	**0.143**	**1.0**	**0.5**	**0.0**	**6.5**
25%	89.75	77.75	88.25	41.75	0.064	0.074	0.117	0.070	0.0	0.0	0.0	0.0
50%	96	94	96.25	93.25	0.306	0.193	0.426	0.271	3.0	19.0	12.8	55.5

Notes: 'Green Minutes' are defined as minutes when PERCLOS 3 was less than 0.12. Under the Feedback Condition, a bottom row green indicator was visible to the subject. 'Yellow+Red Minutes' are defined as minutes when PERCLOS 3 was greater than or equal to 0.12. Under the Feedback Condition, a bottom row yellow or red indicator was visible to the subject.

Table 20
3 Minute PERCLOS
Numbers of Observed and Expected Subset Behaviors When the Indicator was Either Yellow or Red

	P3: Yellow+Red Observed Behaviors				P3: Yellow+Red Expected Behaviors				P3: Yellow+Red Obs. - Exp. Behaviors.			
	Outbound		Inbound		Outbound		Inbound		Outbound		Inbound	
Subject	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control
2001												
2002		0	0	1		0.5	0.3	2.1		-0.5	-0.3	-1.1
2005	2		16		2.2		13.7		-0.2		2.3	
3001												
3003		0		7		0.5		5.3		-0.5		1.7
3004	0		4		1.3		2.8		-1.3		1.3	
3005												
3006	6	3	5	6	0.0	0.0	0.0	0.0	6.0	3.0	5.0	6.0
3007	1	0	11	23	0.8	0.1	10.0	8.9	0.2	-0.1	1.0	14.1
3008	1	14	4	13	0.8	16.4	4.0	44.9	0.2	-2.4	0.0	-31.9
3009	0				0.1				-0.1			
3010		19		20		13.8		25.4		5.2		-5.4
3011												
3012	0	6		28	0.5	2.8		0.0	-0.5	3.2		28.0
3013	0			2	0.2			1.2	-0.2			0.8
3014		2		2		1.0		0.6		1.0		1.4
Median	**0.5**	**2.5**	**4.5**	**7**	**0.6**	**0.8**	**3.4**	**2.1**	**-0.1**	**0.4**	**1.1**	**1.4**
25%	0	0	4	2	0.2	0.4	0.9	0.6	-0.3	-0.5	0.3	-1.1
50%	1.25	8	9.5	20	1.0	5.5	8.5	8.9	0.2	3.1	2.0	6.0

Notes: 'Green Minutes' are defined as minutes when PERCLOS 3 was less than 0.12. Under the Feedback Condition, a bottom row green indicator was visible to the subject. 'Yellow+Red Minutes' are defined as minutes when PERCLOS 3 was greater than or equal to 0.21. Under the Feedback Condition, a bottom row yellow or red indicator was visible to the subject.

Table 21
3 Minute PERCLOS
Numbers of Minutes and Subset Behaviors per Minute When Indicator Was Green and the Number of Minutes Indicator was Red

	Green Minutes				**Green Behavior Rate**				**Red Minutes**			
	Outbound		**Inbound**		**Outbound**		**Inbound**		**Outbound**		**Inbound**	
Subject	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control
2001	79	93	120	93	0.025	0.086	0.208	0.075	0	0	0	0
2002	104	94	91	92	0.135	0.543	0.330	0.304	0	0	0	0
2005	67	93	63	94	0.090	0.097	0.508	0.053	1	0	3	0
3001	96	91	99	91	0.146	0.187	0.131	0.132	0	0	0	0
3003	101	87	107	48	0.059	0.057	0.093	0.104	0	0	0	20
3004	93	98	72	96	0.258	0.112	0.125	0.240	0	0	0	0
3005	93	95	91	96	0.097	0.116	0.264	0.260	0	0	0	0
3006	4	11	2	2	0.000	0.000	0.000	0.000	53	20	84	49
3007	106	103	92	61	0.283	0.078	0.554	0.197	0	0	0	9
3008	90	37	80	20	0.378	0.297	0.363	0.650	0	17	0	40
3009	93	92	92	91	0.065	0.098	0.087	0.154	0	0	0	0
3010	95	33	93	23	0.474	0.212	0.398	0.348	0	2	0	28
3011	93	94	94	90	0.398	0.309	0.713	0.389	0	0	0	0
3012	91	50	97	4	0.176	0.060	0.361	0.000	0	1	0	20
3013	89	93	92	71	0.056	0.032	0.054	0.042	0	0	0	0
3014	96	88	96	94	0.375	0.102	0.531	0.096	0	0	0	0
Median	**93**	**92.5**	**92**	**90.5**	**0.141**	**0.100**	**0.297**	**0.143**	**0.0**	**0.0**	**0.0**	**0.0**
25%	89.75	77.75	88.25	41.75	0.064	0.074	0.117	0.070	0.0	0.0	0.0	0.0
50%	96	94	96.25	93.25	0.306	0.193	0.426	0.271	0.0	0.3	0.0	20.0

Notes: 'Green Minutes' are defined as minutes when PERCLOS 3 was less than 0.12. Under the Feedback Condition, a bottom row green indicator was visible to the subject. 'Red Minutes' are defined as minutes when PERCLOS 3 was greater than or equal to 0.21. Under the Feedback Condition, a bottom row red indicator was visible to the subject.

Table 22

3 Minute PERCLOS
Numbers of Observed and Expected Subset Behaviors When the Indicator was Red

	P3: Red Observed Behaviors				P3: Red Expected Behaviors				P3: Red Obs. - Exp. Behaviors.			
	Outbound		Inbound		Outbound		Inbound		Outbound		Inbound	
Subject	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control	Feedback	Control
2001												
2002												
2005	0		3		0.1		1.5		-0.1		1.5	
3001												
3003				3				2.1				0.9
3004												
3005												
3006	2	0	5	5	0.0	0.0	0.0	0.0	2.0	0.0	5.0	5.0
3007				6				1.8				4.2
3008		3		7		5.1		26.0		-2.1		-19.0
3009												
3010		0		6		0.4		9.7		-0.4		-3.7
3011												
3012		1		7		0.1		0.0		0.9		7.0
3013												
3014												
Median	**1**	**0.5**	**4**	**6**	**0.0**	**0.2**	**0.8**	**1.9**	**1.0**	**-0.2**	**3.2**	**2.6**
25%	0.5	0	3.5	5.25	0.0	0.0	0.4	0.4	0.4	-0.8	2.4	-2.6
50%	1.5	1.5	4.5	6.75	0.1	1.6	1.1	7.8	1.5	0.2	4.1	4.8

Notes: 'Green Minutes' are defined as minutes when PERCLOS 3 was less than 0.12. Under the Feedback Condition, a bottom row green indicator was visible to the subject. 'Red Minutes' are defined as minutes when PERCLOS 3 was greater than or equal to 0.21. Under the Feedback Condition, a bottom row red indicator was visible to the subject.

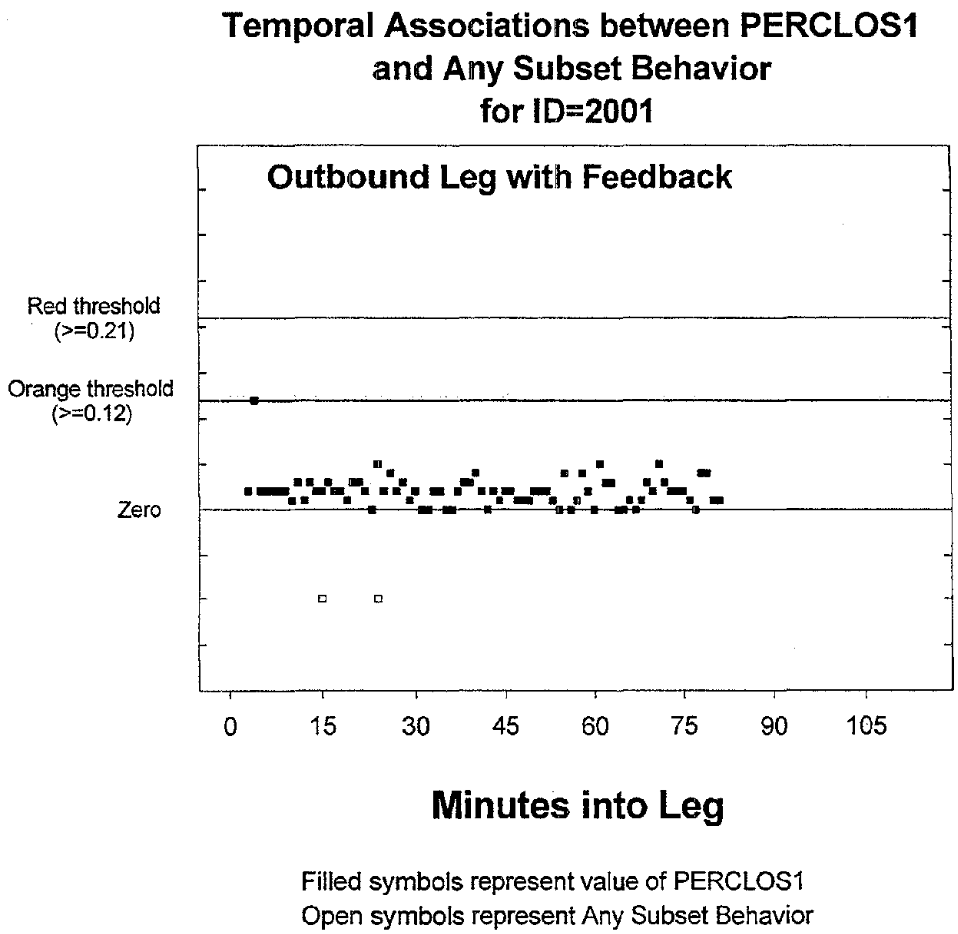

Figure 26. Temporal relationship for subject 2001 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the outbound leg of the nighttime drive in which PERCLOS feedback was provided.

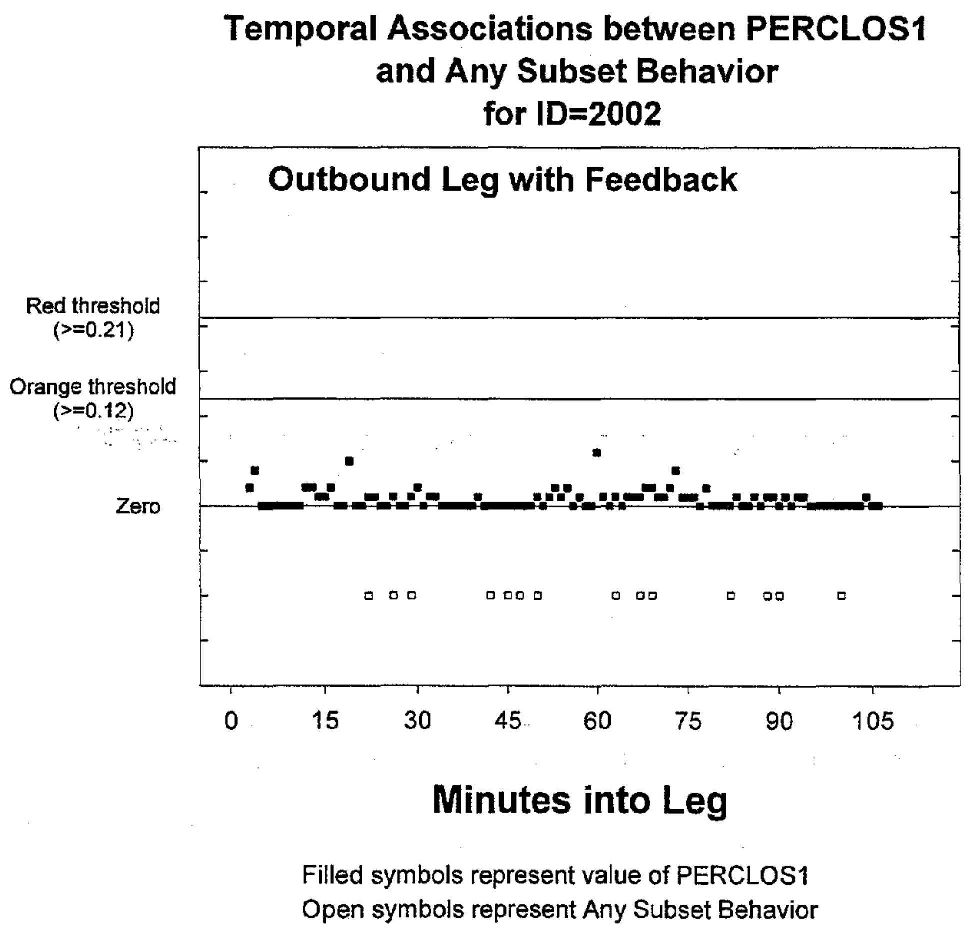

Figure 27. Temporal relationship for subject 2002 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the outbound leg of the nighttime drive in which PERCLOS feedback was provided.

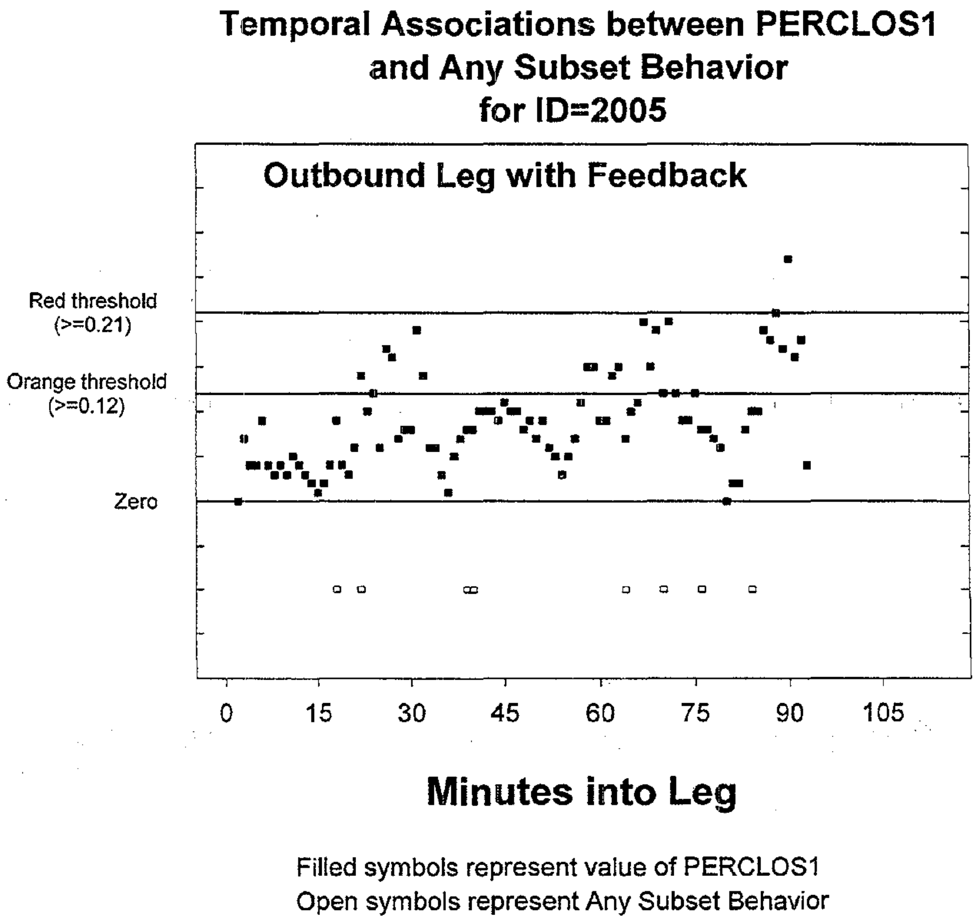

Figure 28. Temporal relationship for subject 2005 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the outbound leg of the nighttime drive in which PERCLOS feedback was provided.

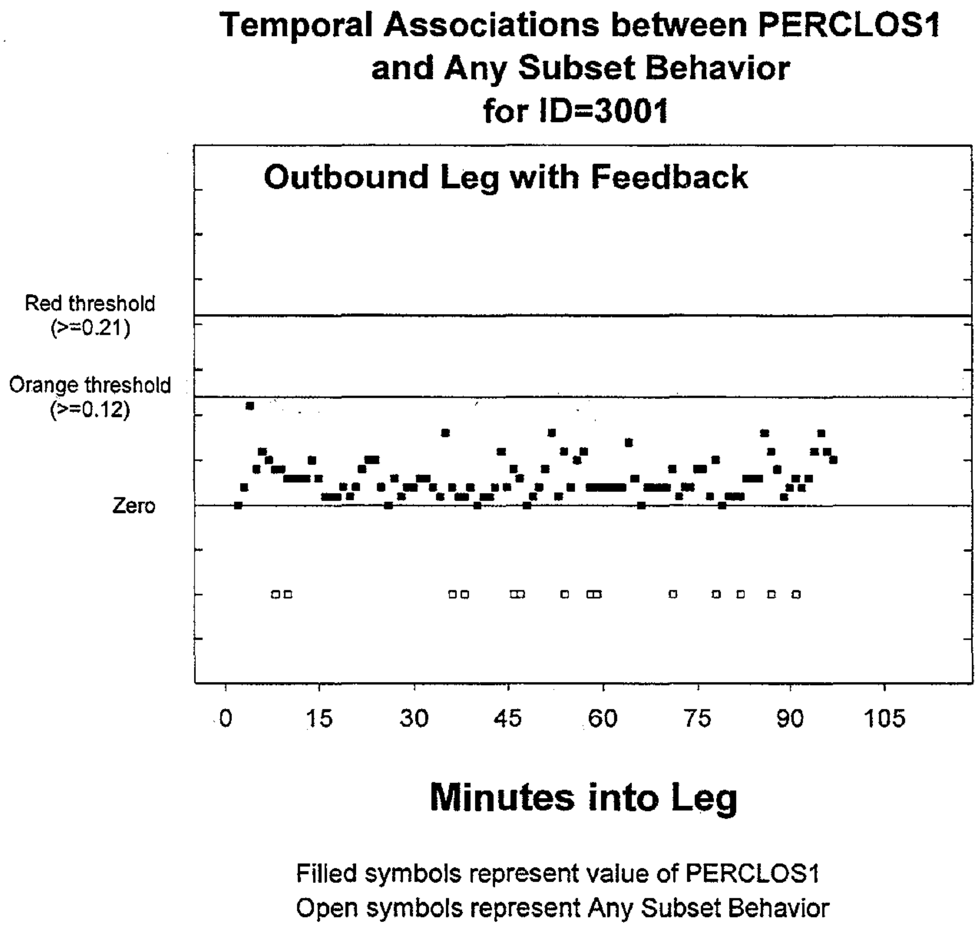

Figure 29. Temporal relationship for subject 3001 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the outbound leg of the nighttime drive in which PERCLOS feedback was provided.

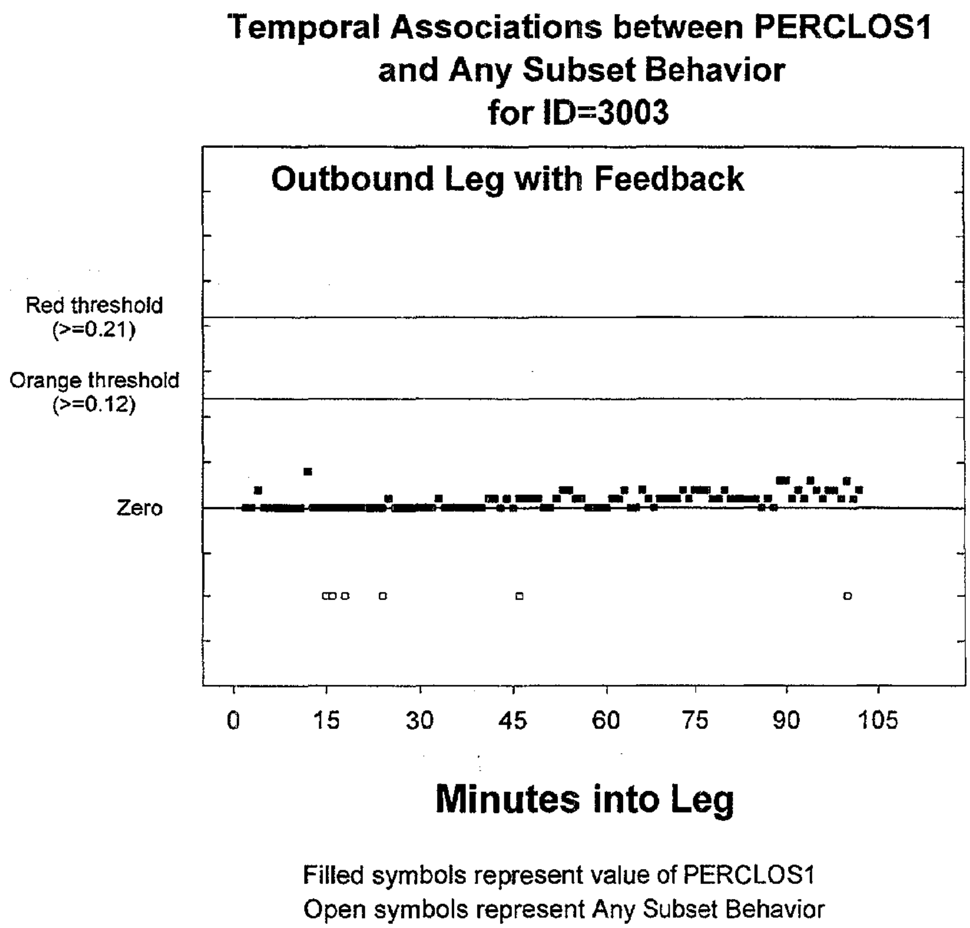

Figure 30. Temporal relationship for subject 3003 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the outbound leg of the nighttime drive in which PERCLOS feedback was provided.

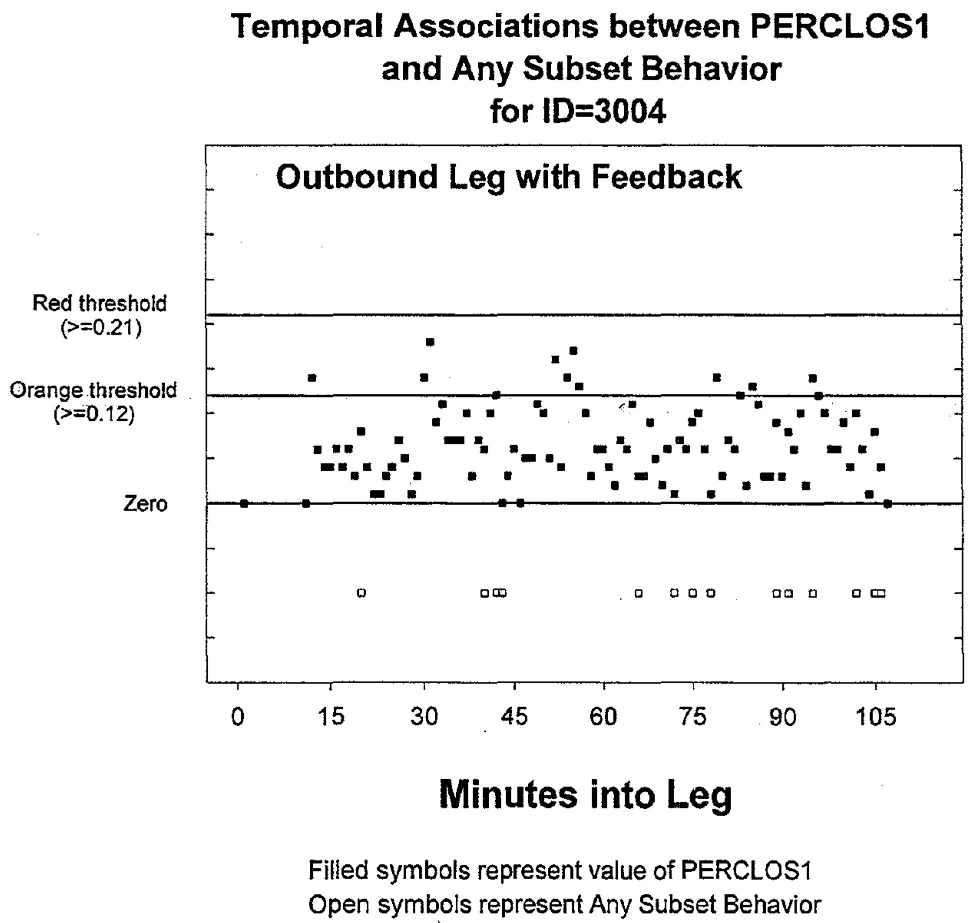

Figure 31. Temporal relationship for subject 3004 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the outbound leg of the nighttime drive in which PERCLOS feedback was provided.

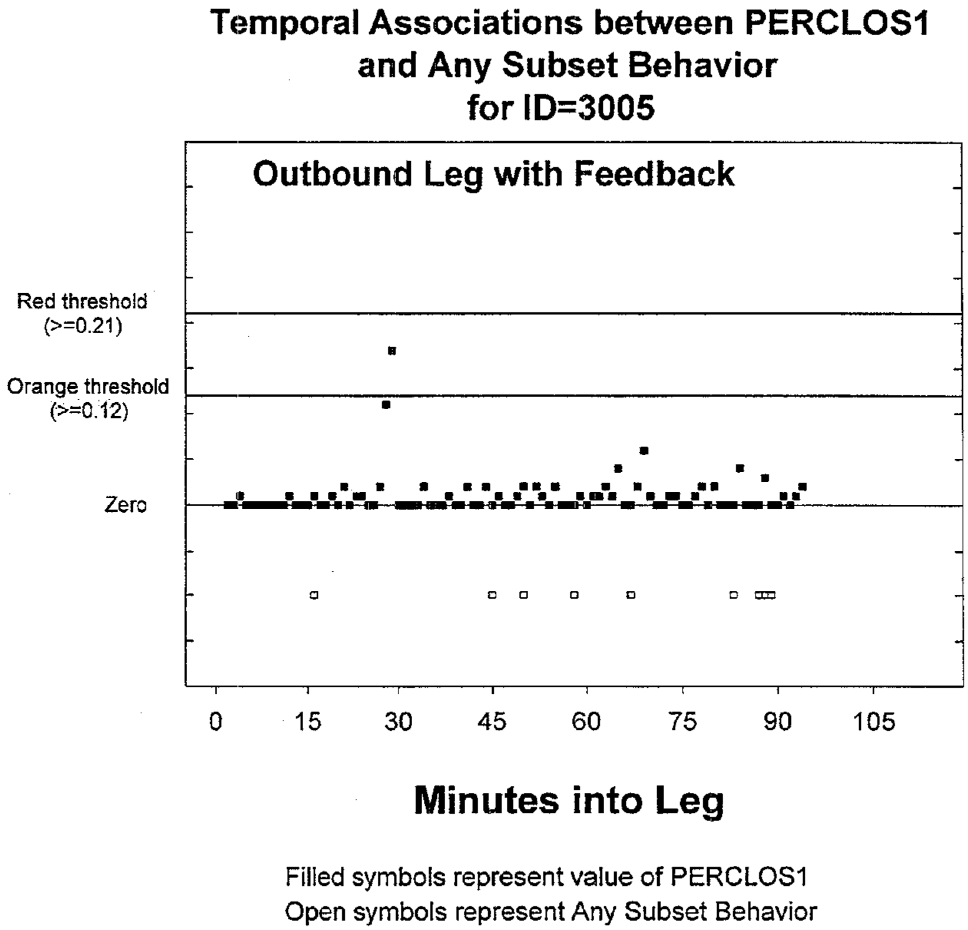

Figure 32. Temporal relationship for subject 3005 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the outbound leg of the nighttime drive in which PERCLOS feedback was provided.

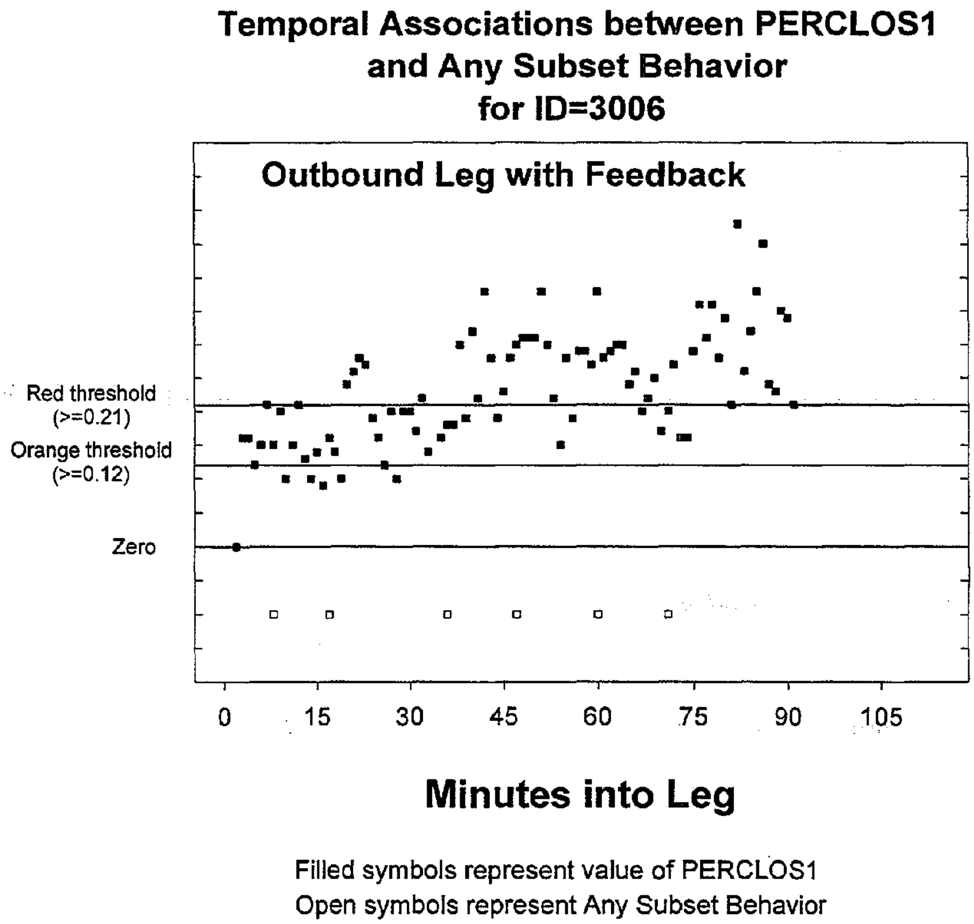

Figure 33. Temporal relationship for subject 3006 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the outbound leg of the nighttime drive in which PERCLOS feedback was provided.

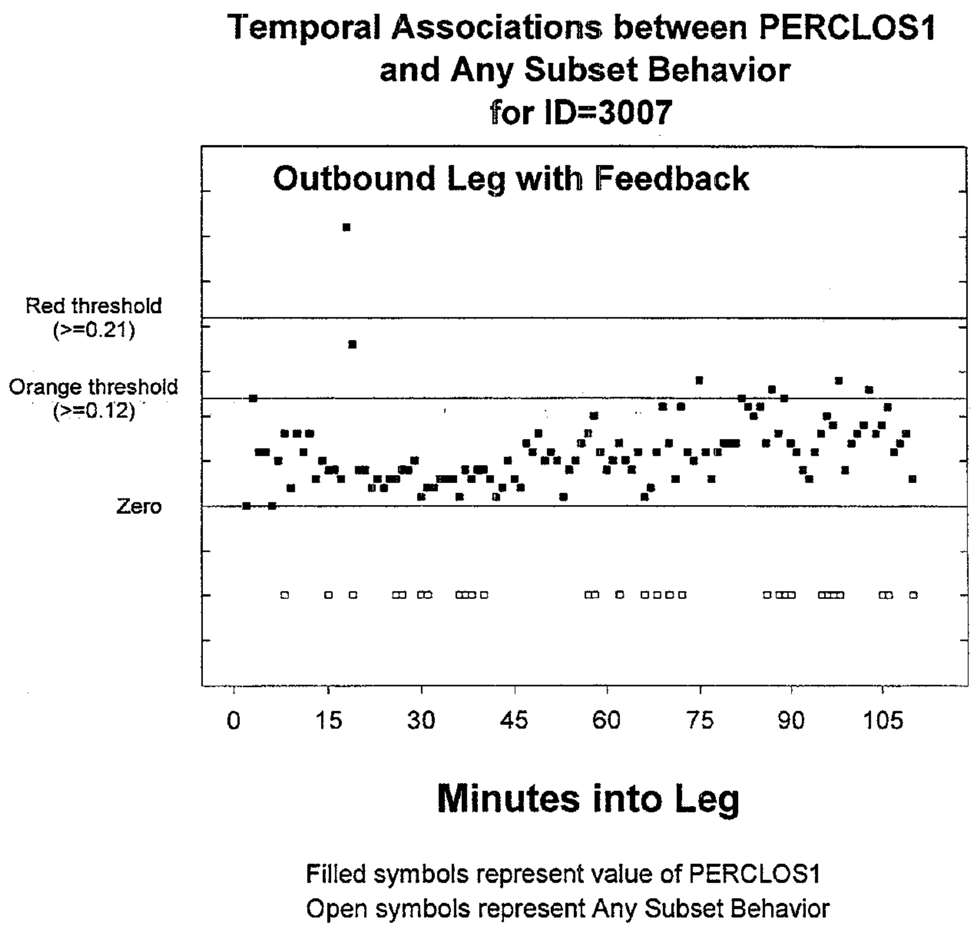

Figure 34. Temporal relationship for subject 3007 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the outbound leg of the nighttime drive in which PERCLOS feedback was provided.

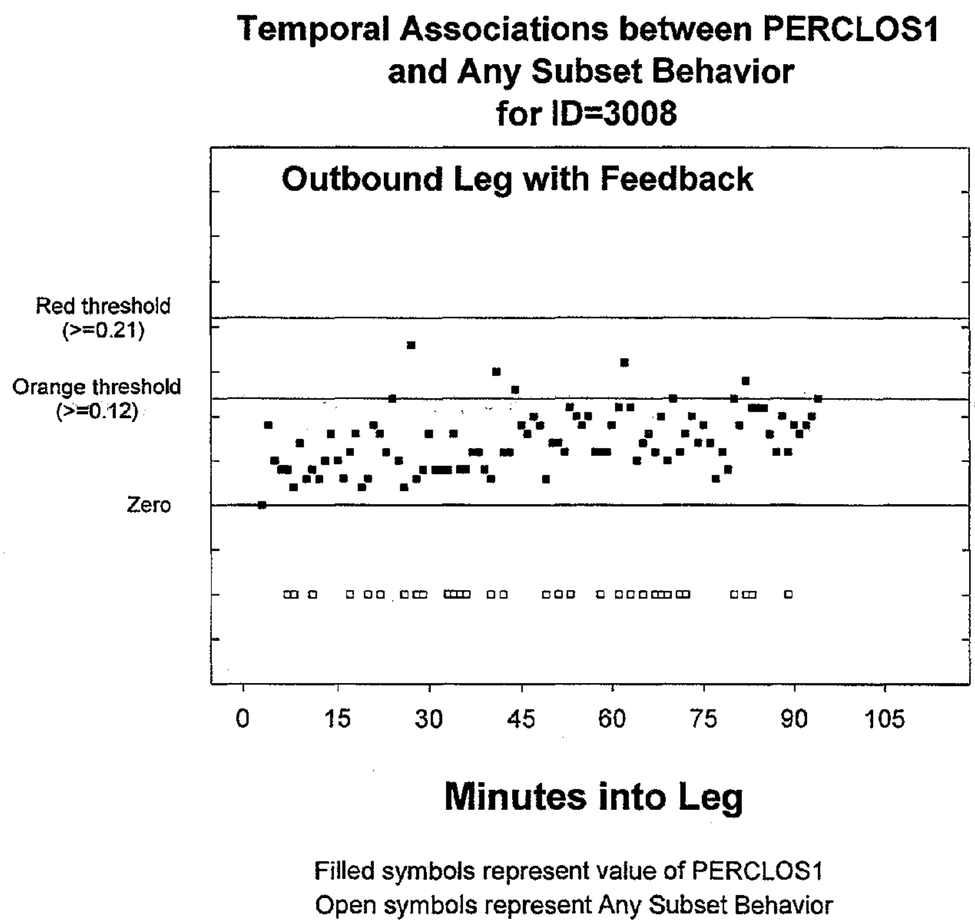

Figure 35. Temporal relationship for subject 3008 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the outbound leg of the nighttime drive in which PERCLOS feedback was provided.

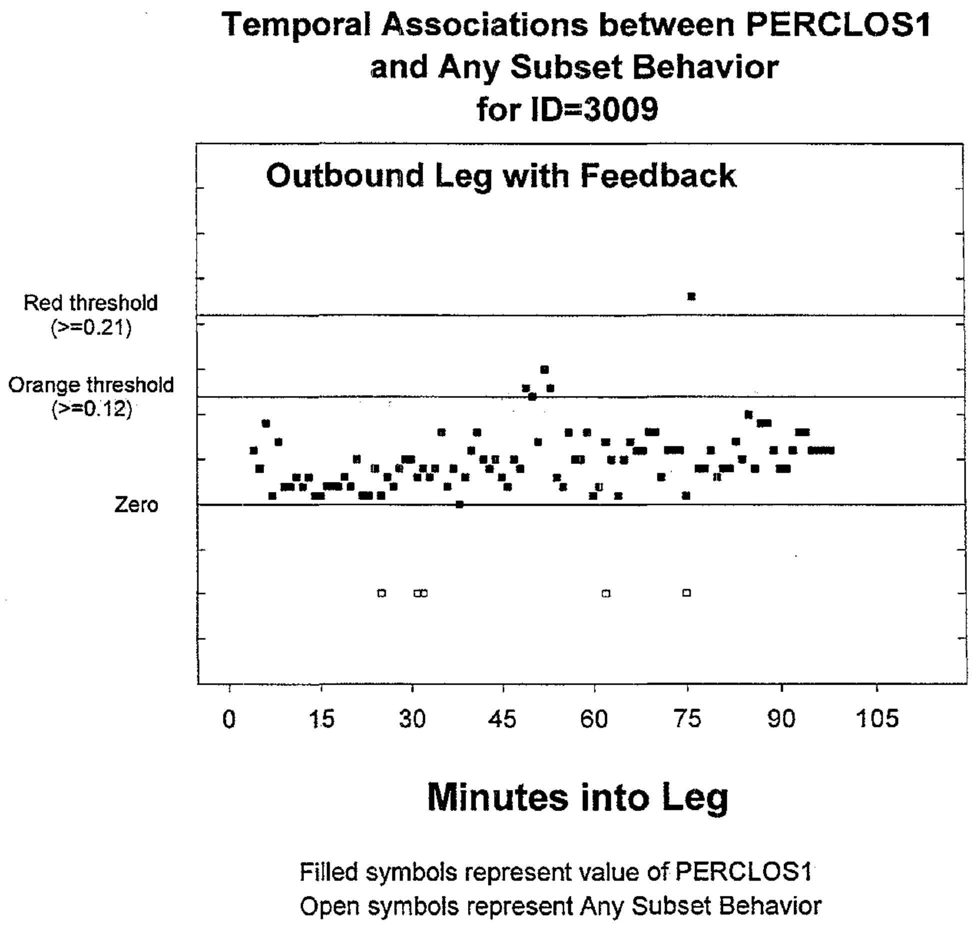

Figure 36. Temporal relationship for subject 3009 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the outbound leg of the nighttime drive in which PERCLOS feedback was provided.

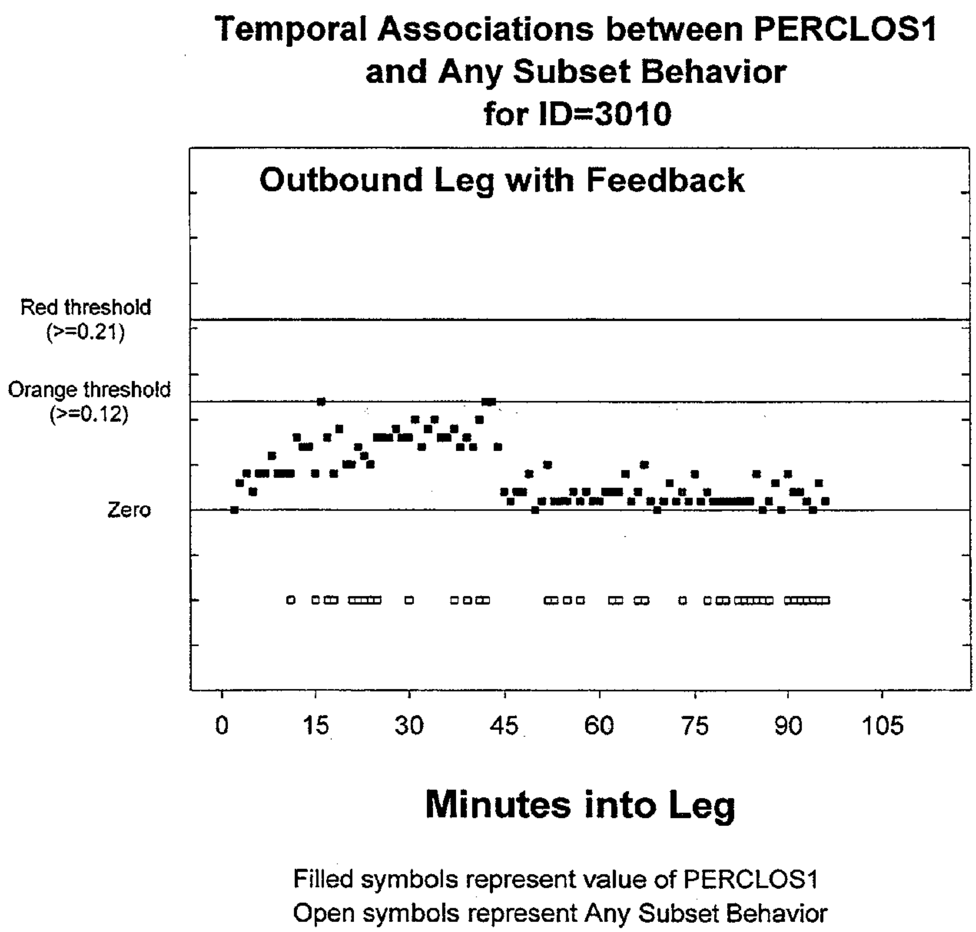

Figure 37. Temporal relationship for subject 3010 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the outbound leg of the nighttime drive in which PERCLOS feedback was provided.

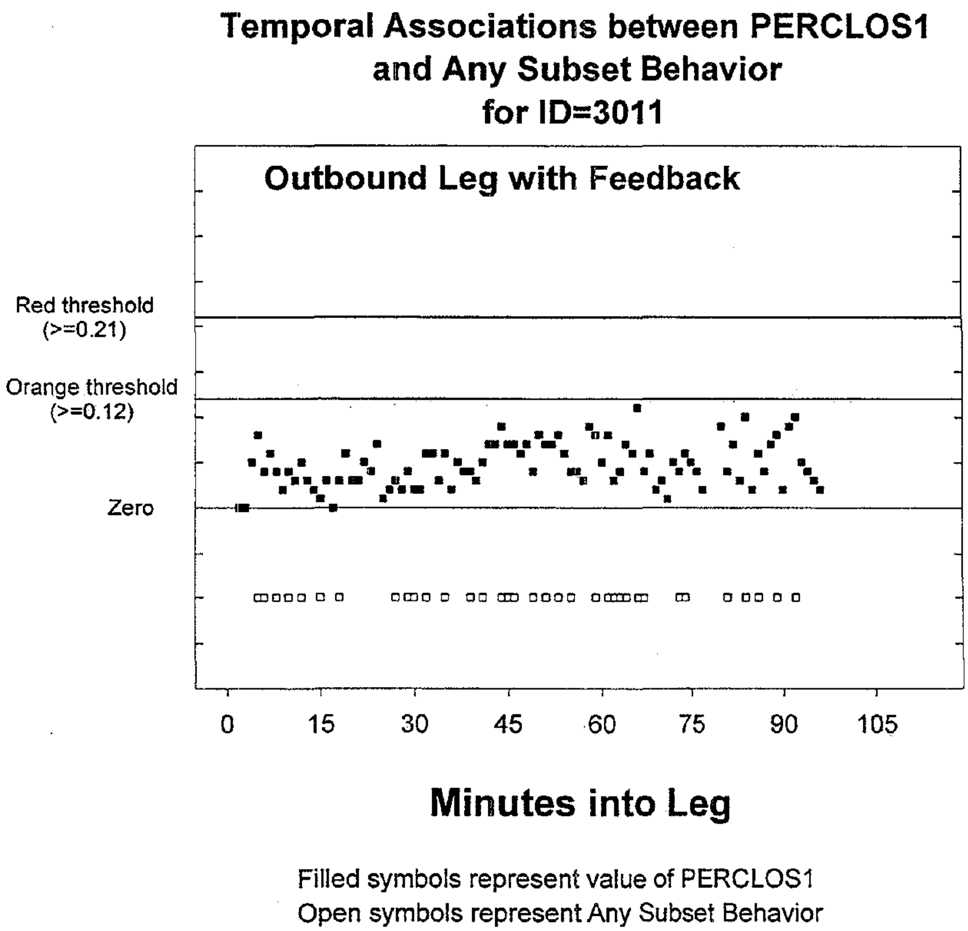

Figure 38. Temporal relationship for subject 3011 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the outbound leg of the nighttime drive in which PERCLOS feedback was provided.

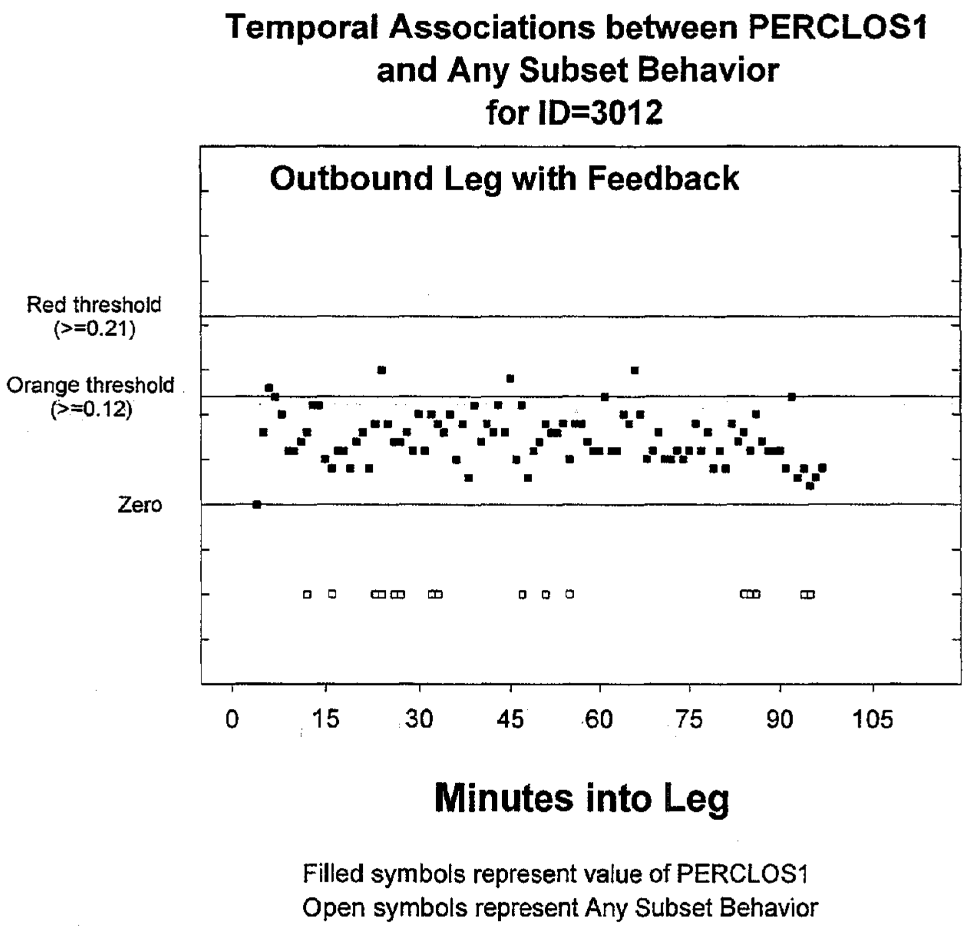

Figure 39. Temporal relationship for subject 3012 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the outbound leg of the nighttime drive in which PERCLOS feedback was provided.

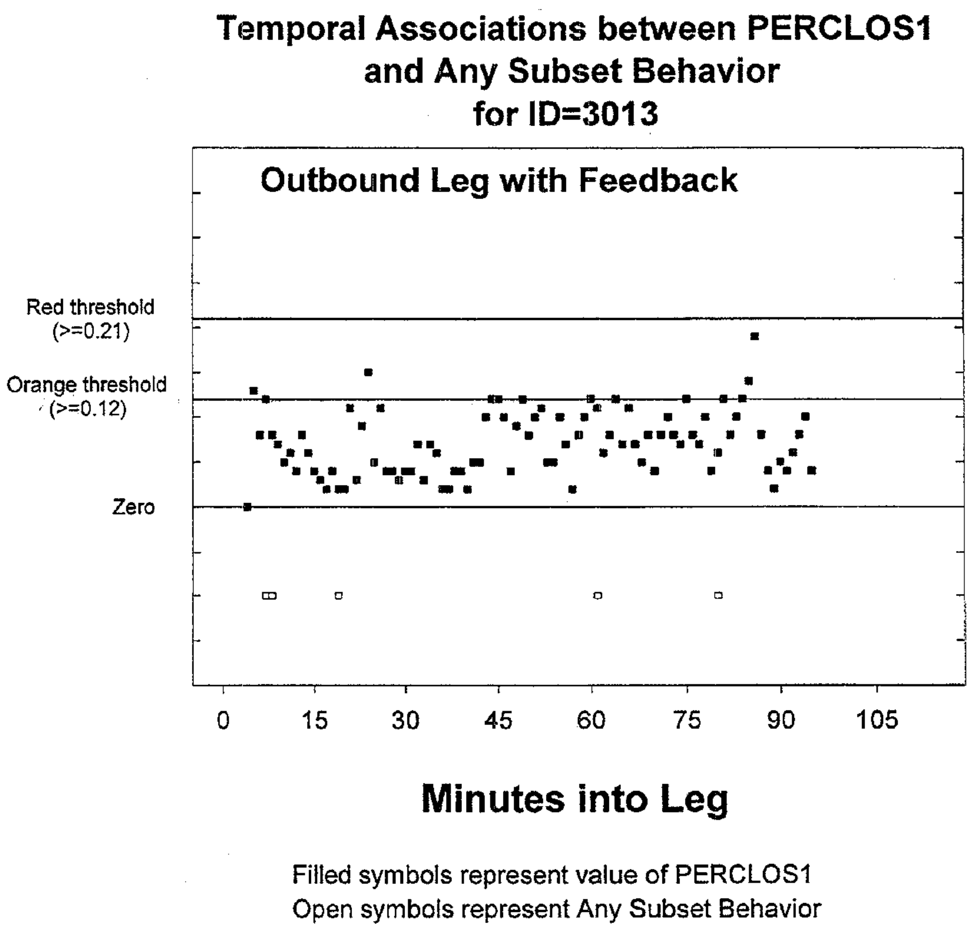

Figure 40. Temporal relationship for subject 3013 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the outbound leg of the nighttime drive in which PERCLOS feedback was provided.

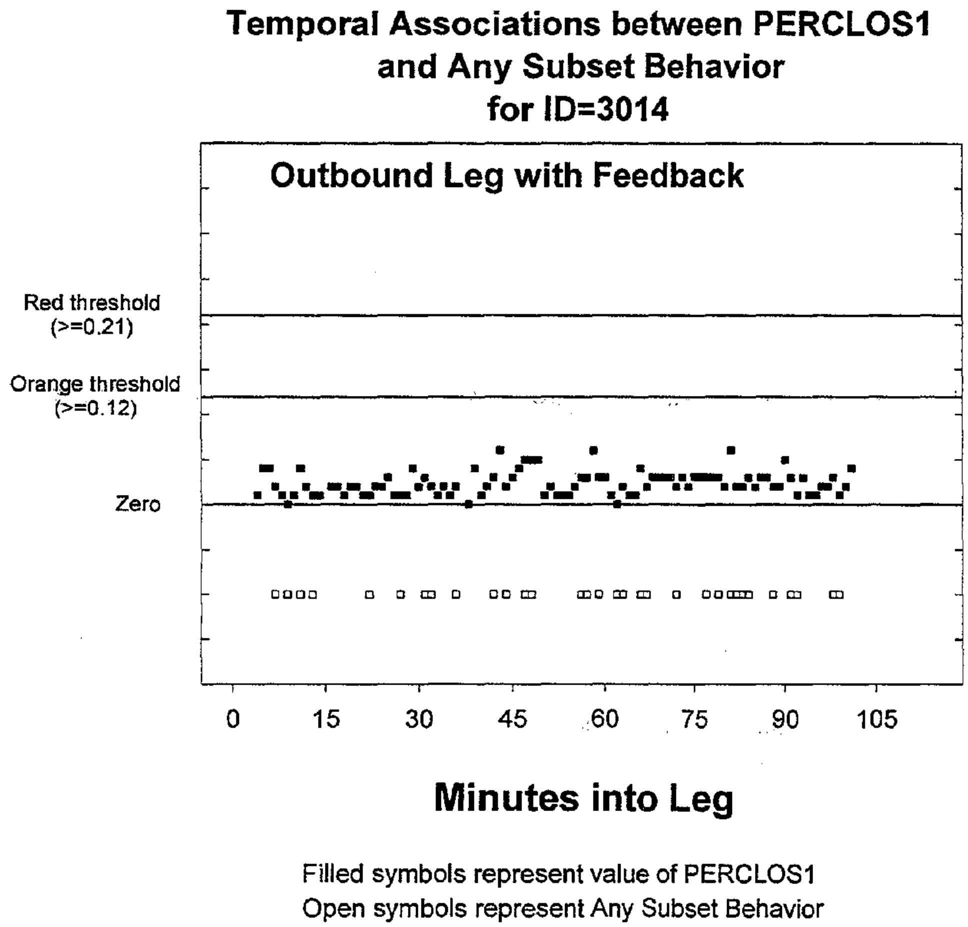

Figure 41. Temporal relationship for subject 3014 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the outbound leg of the nighttime drive in which PERCLOS feedback was provided.

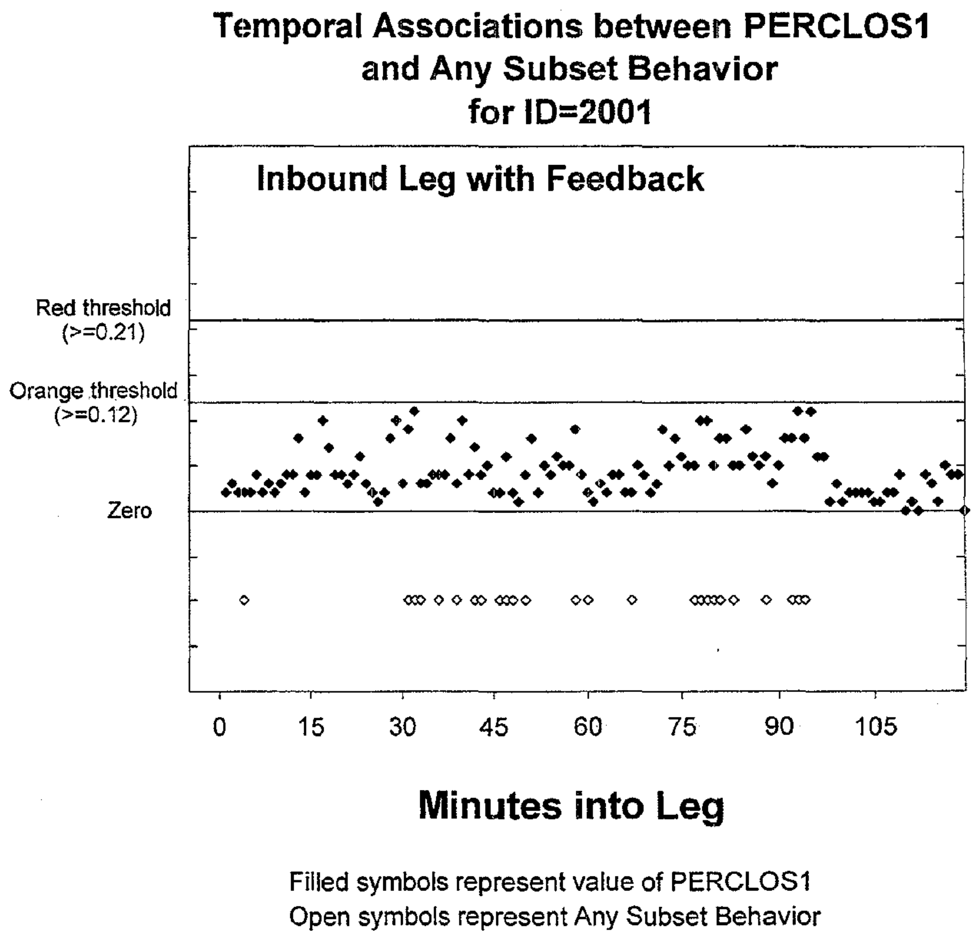

Figure 42. Temporal relationship for subject 2001 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the inbound leg of the nighttime drive in which PERCLOS feedback was provided.

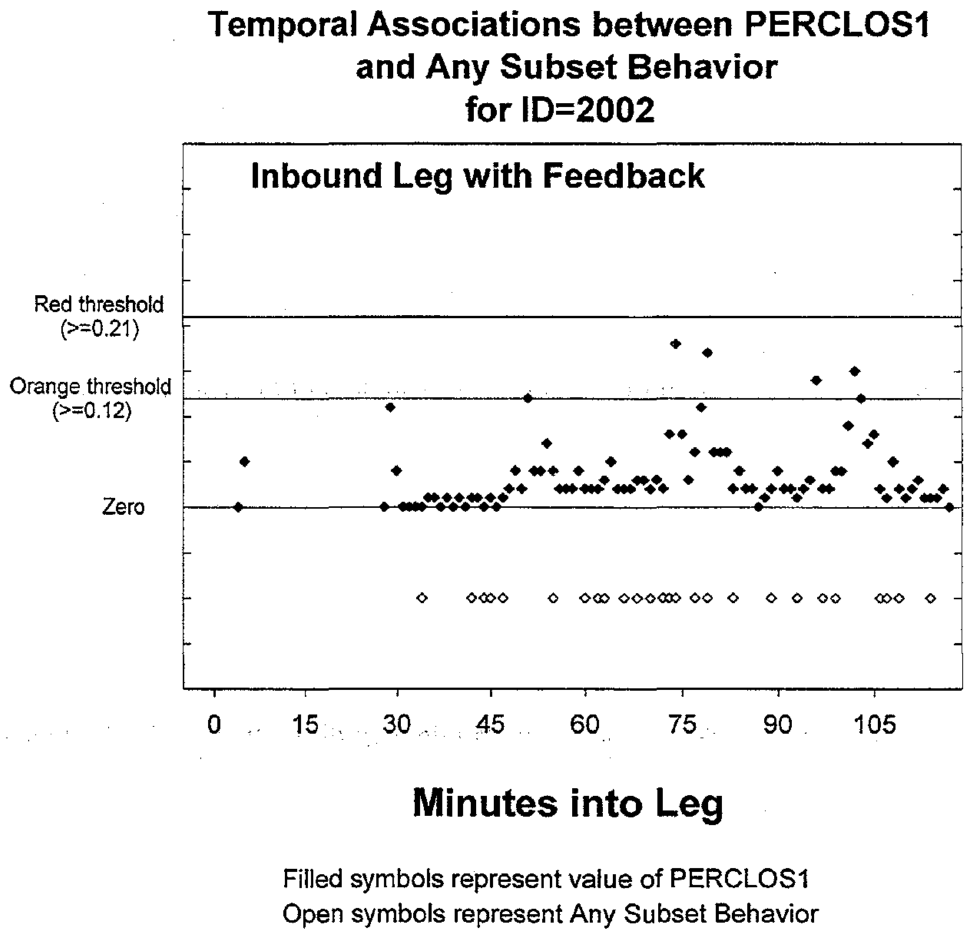

Figure 43. Temporal relationship for subject 2002 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the inbound leg of the nighttime drive in which PERCLOS feedback was provided.

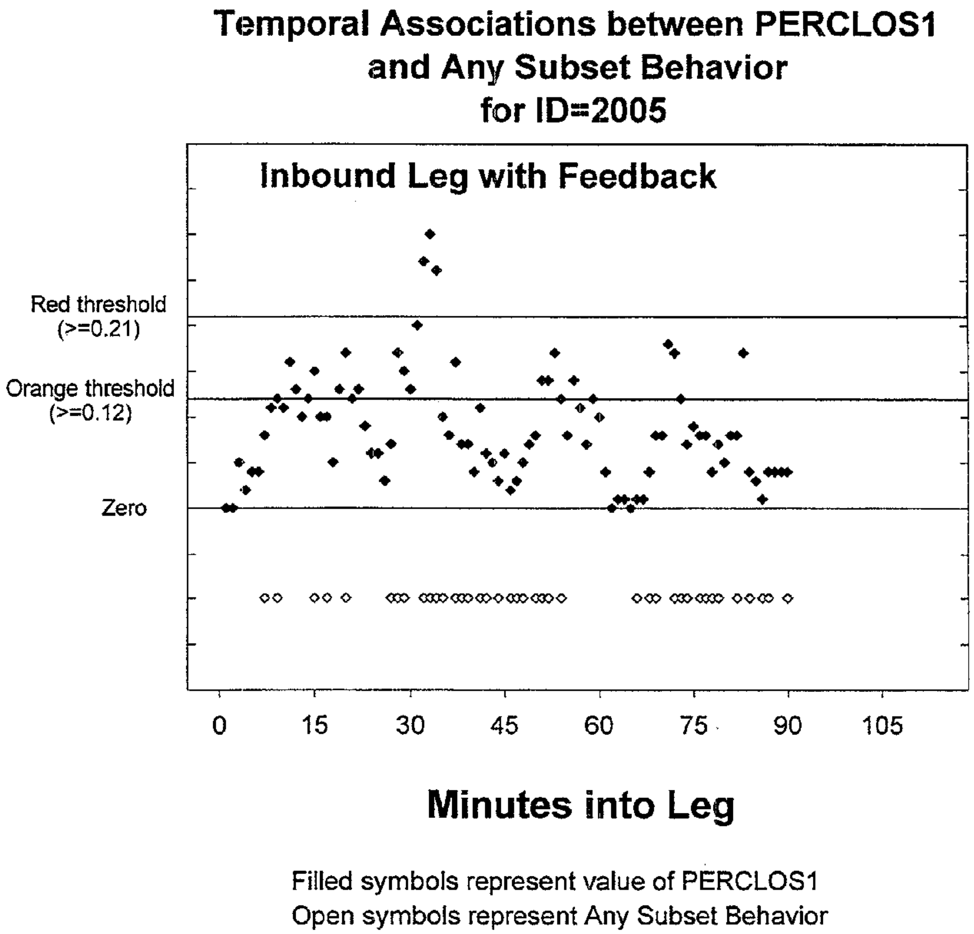

Figure 44. Temporal relationship for subject 2005 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the inbound leg of the nighttime drive in which PERCLOS feedback was provided.

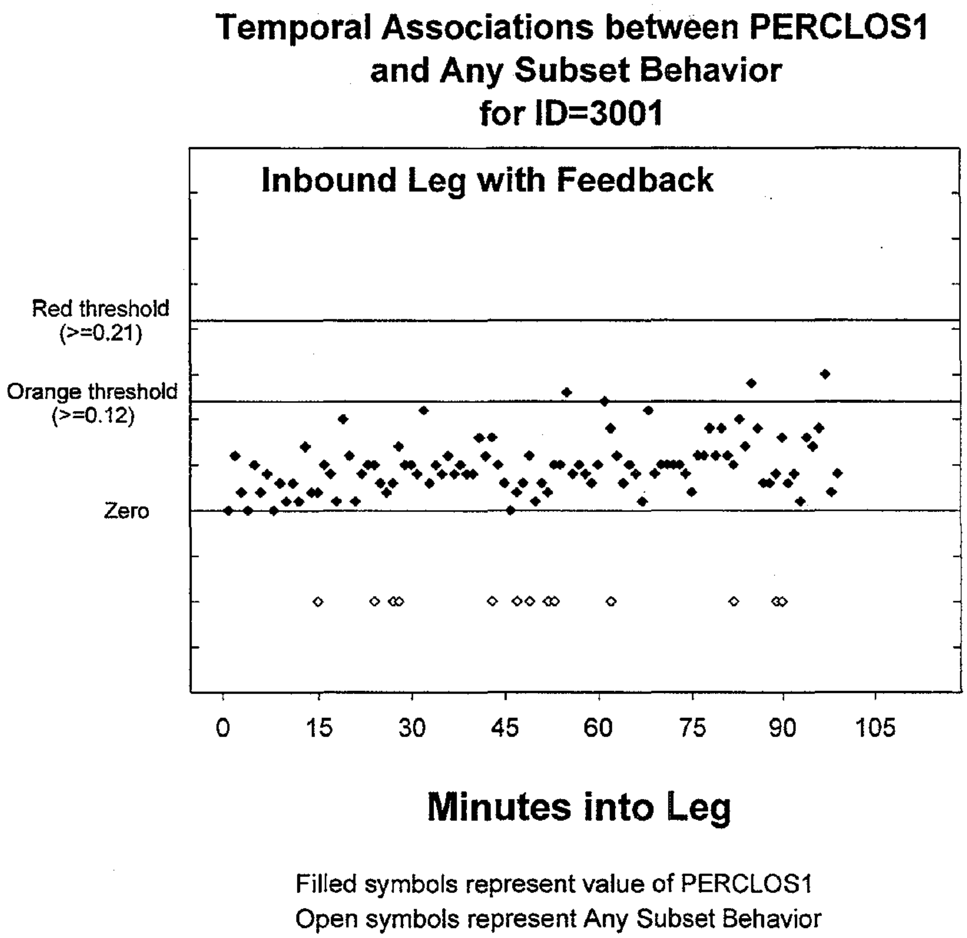

Figure 45. Temporal relationship for subject 3001 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the inbound leg of the nighttime drive in which PERCLOS feedback was provided.

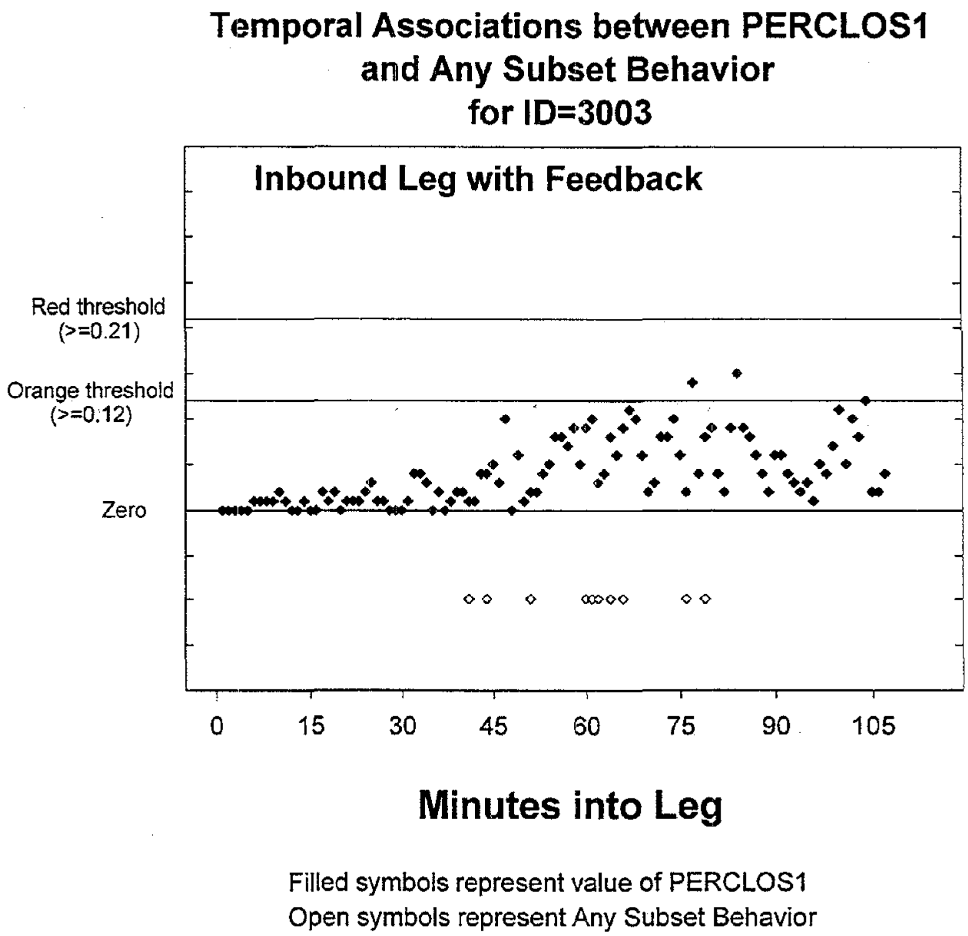

Figure 46. Temporal relationship for subject 3003 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the inbound leg of the nighttime drive in which PERCLOS feedback was provided.

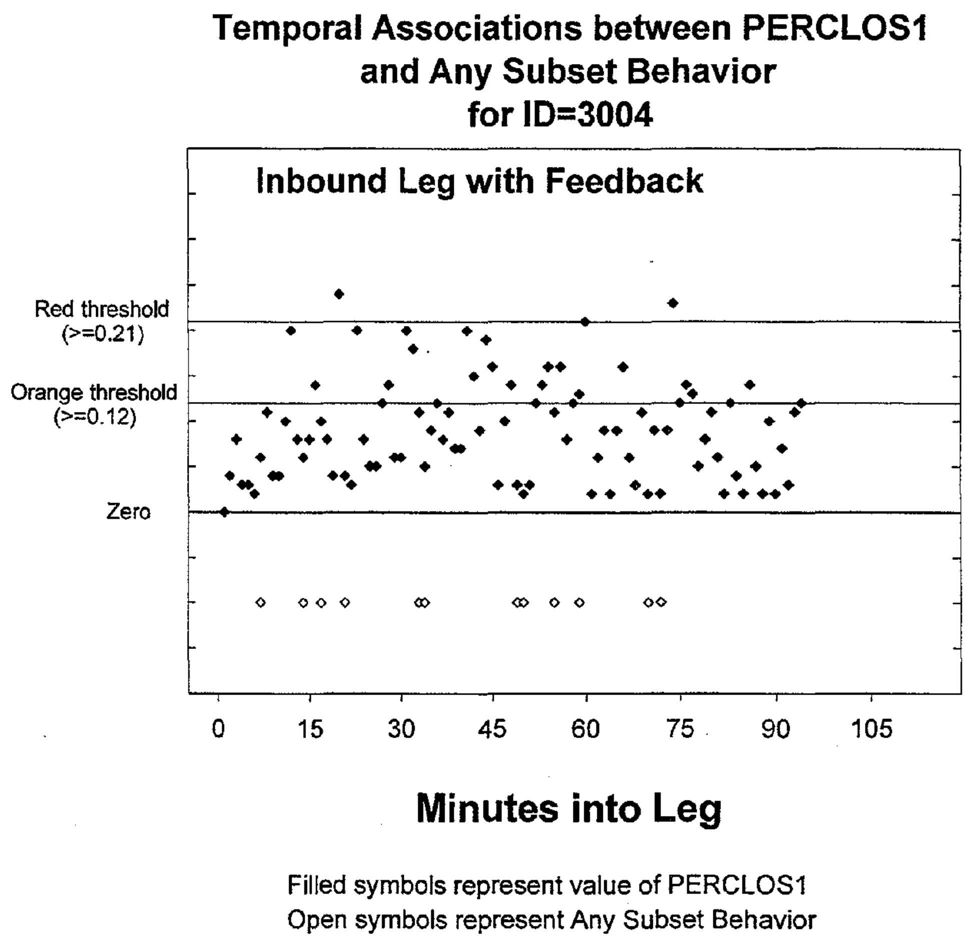

Figure 47. Temporal relationship for subject 3004 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the inbound leg of the nighttime drive in which PERCLOS feedback was provided.

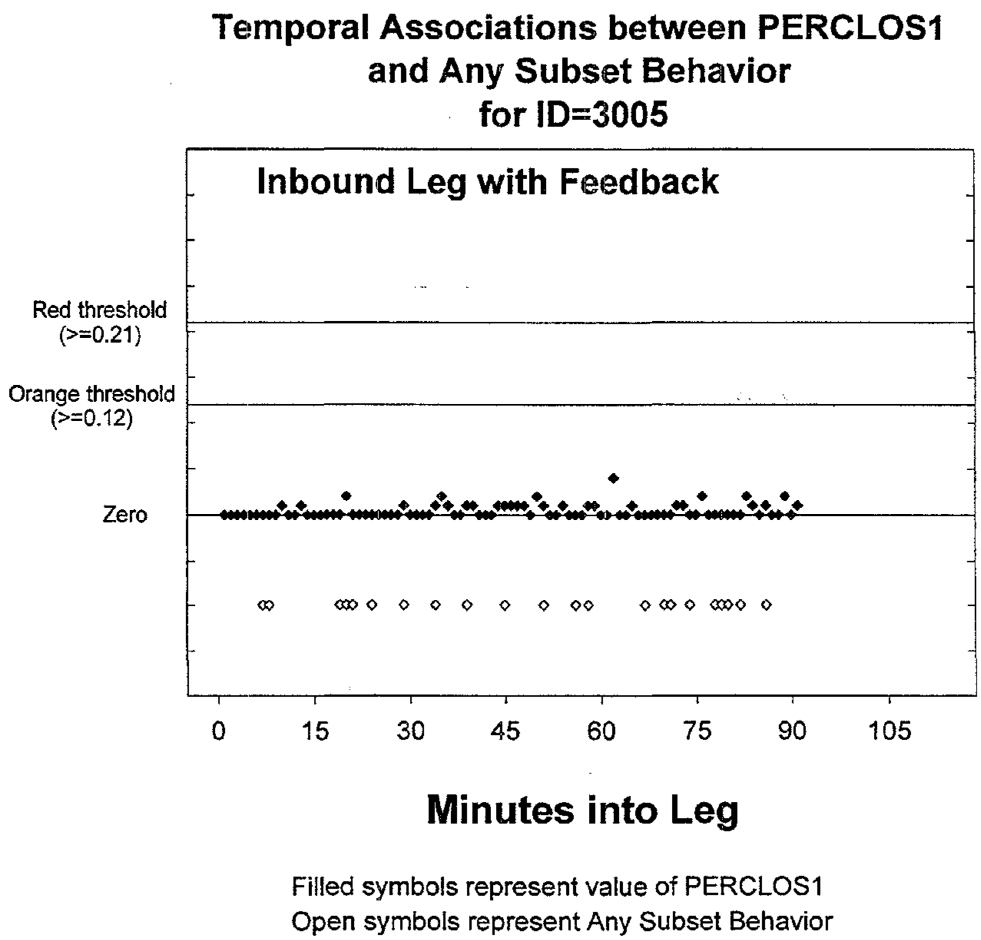

Figure 48. Temporal relationship for subject 3005 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the inbound leg of the nighttime drive in which PERCLOS feedback was provided.

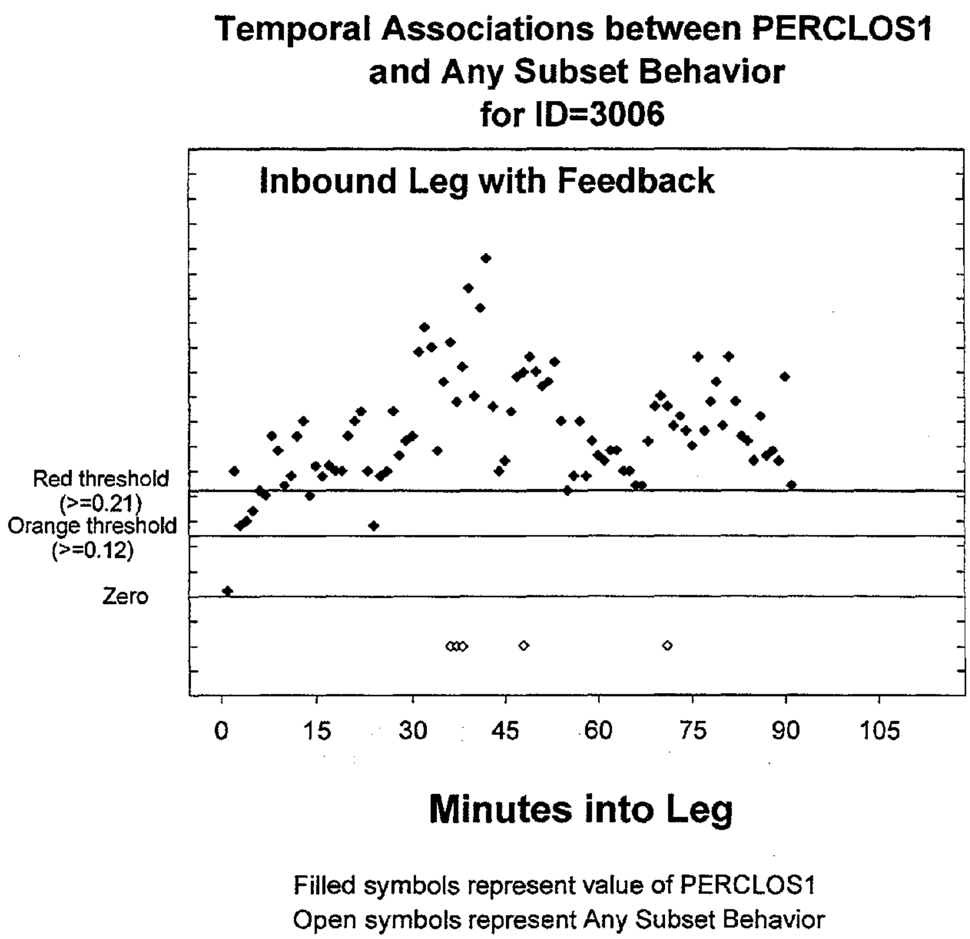

Figure 49. Temporal relationship for subject 3006 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the inbound leg of the nighttime drive in which PERCLOS feedback was provided.

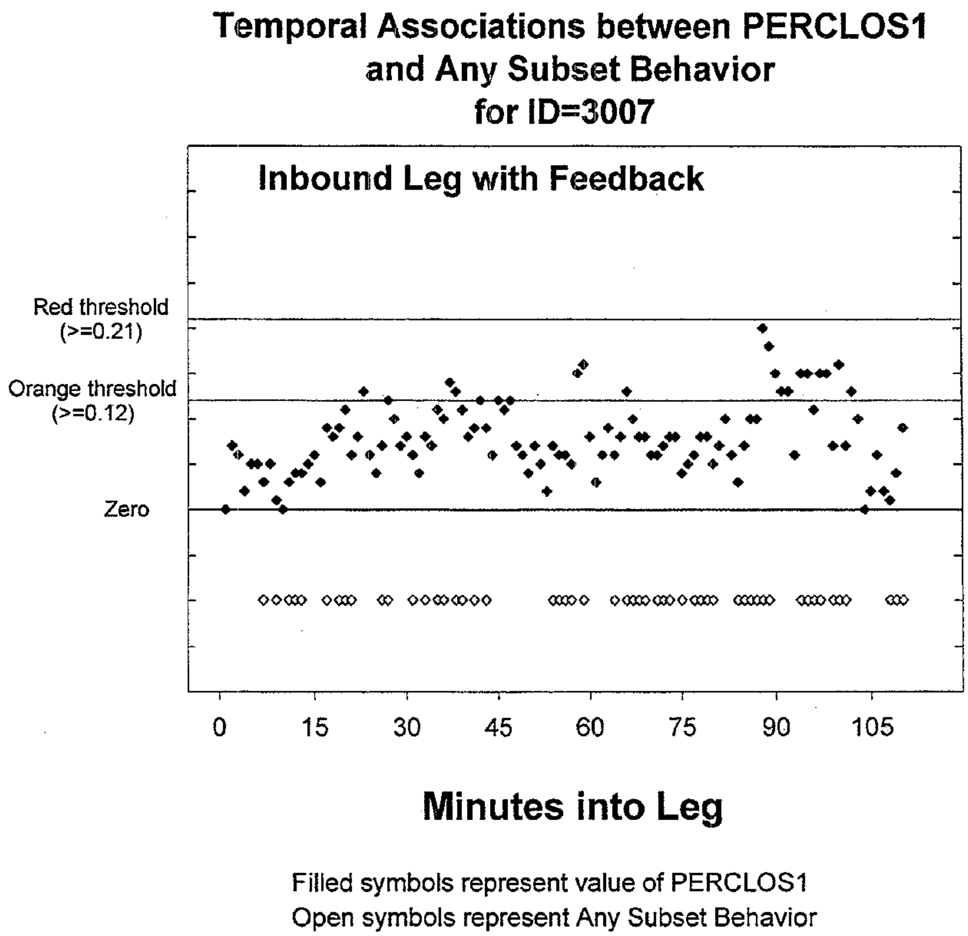

Figure 50. Temporal relationship for subject 3007 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the inbound leg of the nighttime drive in which PERCLOS feedback was provided.

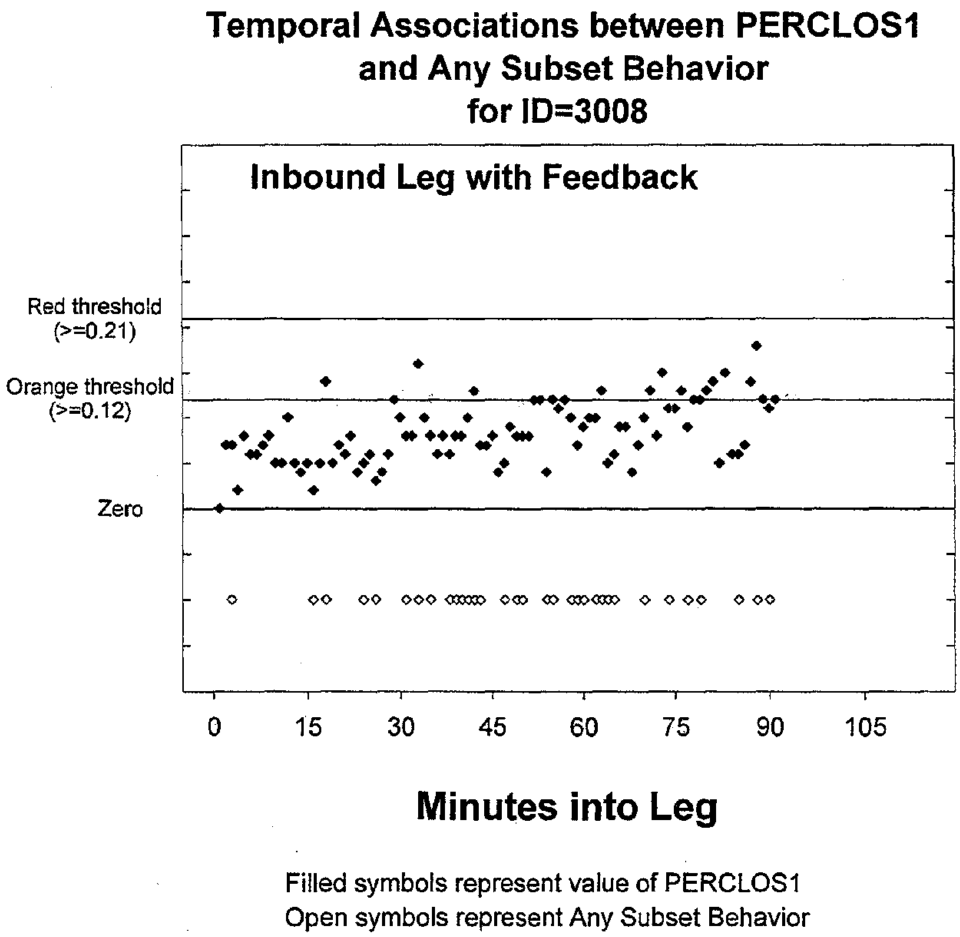

Figure 51. Temporal relationship for subject 3008 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the inbound leg of the nighttime drive in which PERCLOS feedback was provided.

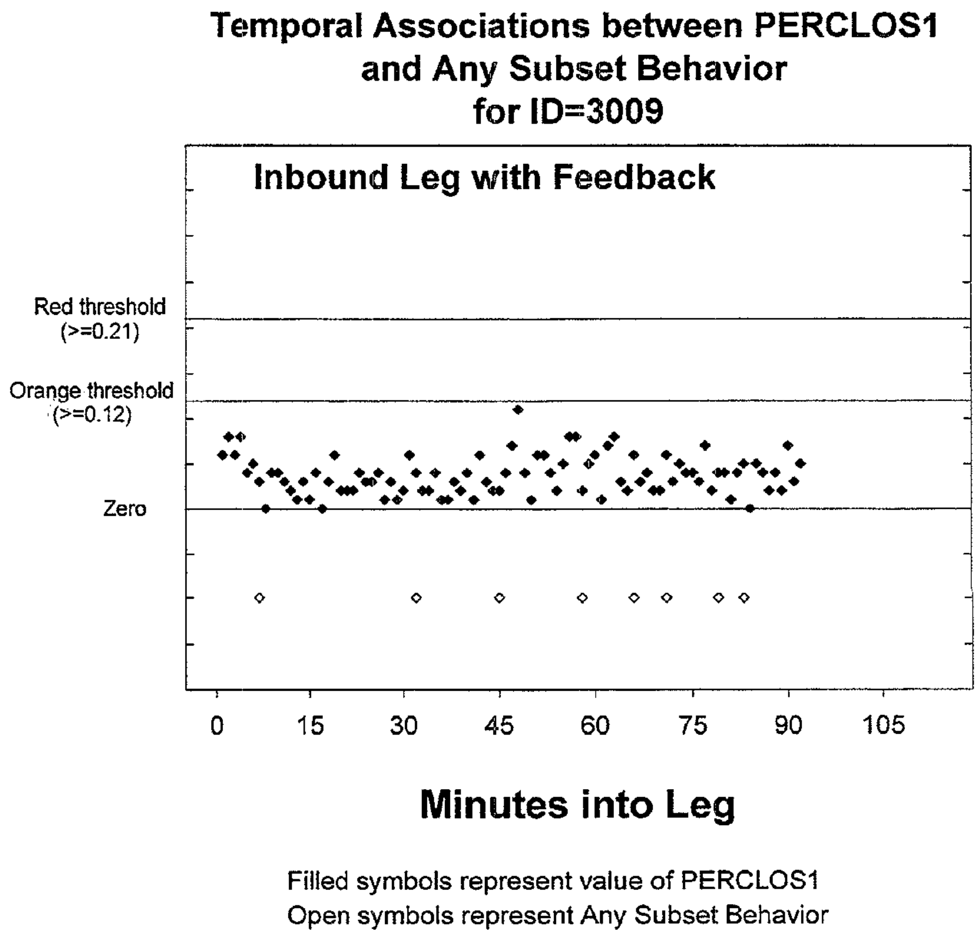

Figure 52. Temporal relationship for subject 3009 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the inbound leg of the nighttime drive in which PERCLOS feedback was provided.

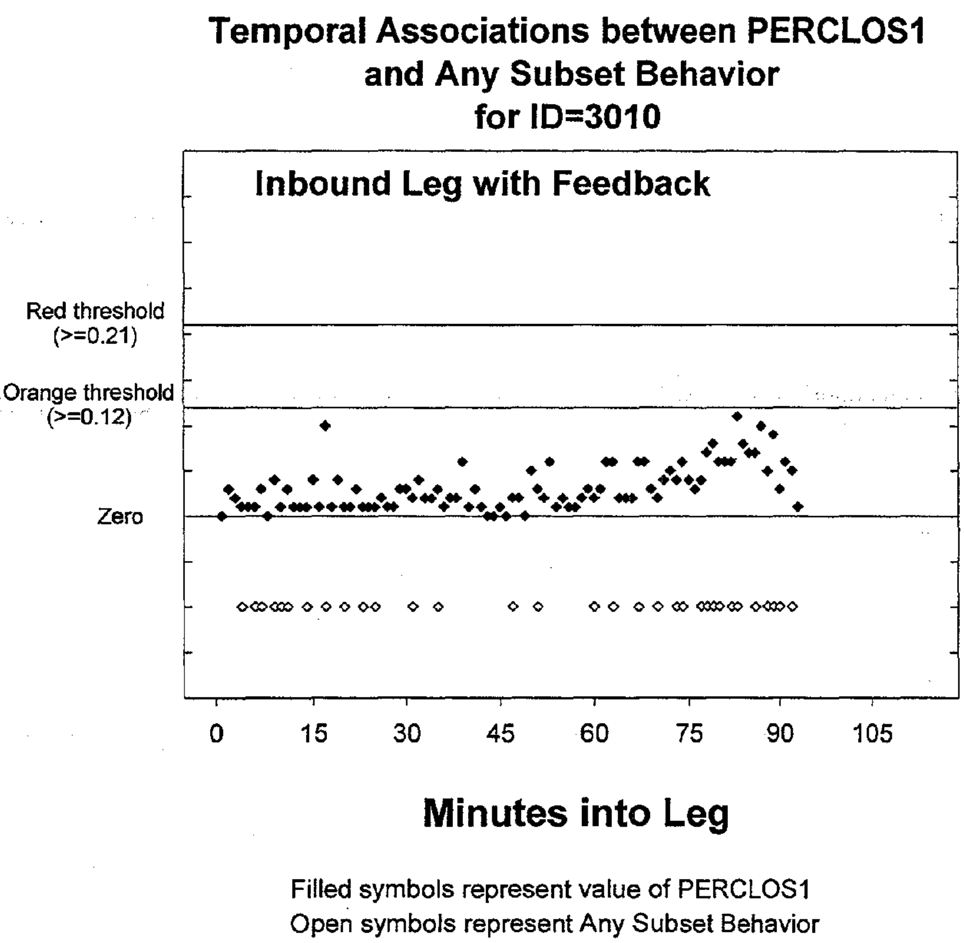

Figure 53. Temporal relationship for subject 3010 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the inbound leg of the nighttime drive in which PERCLOS feedback was provided.

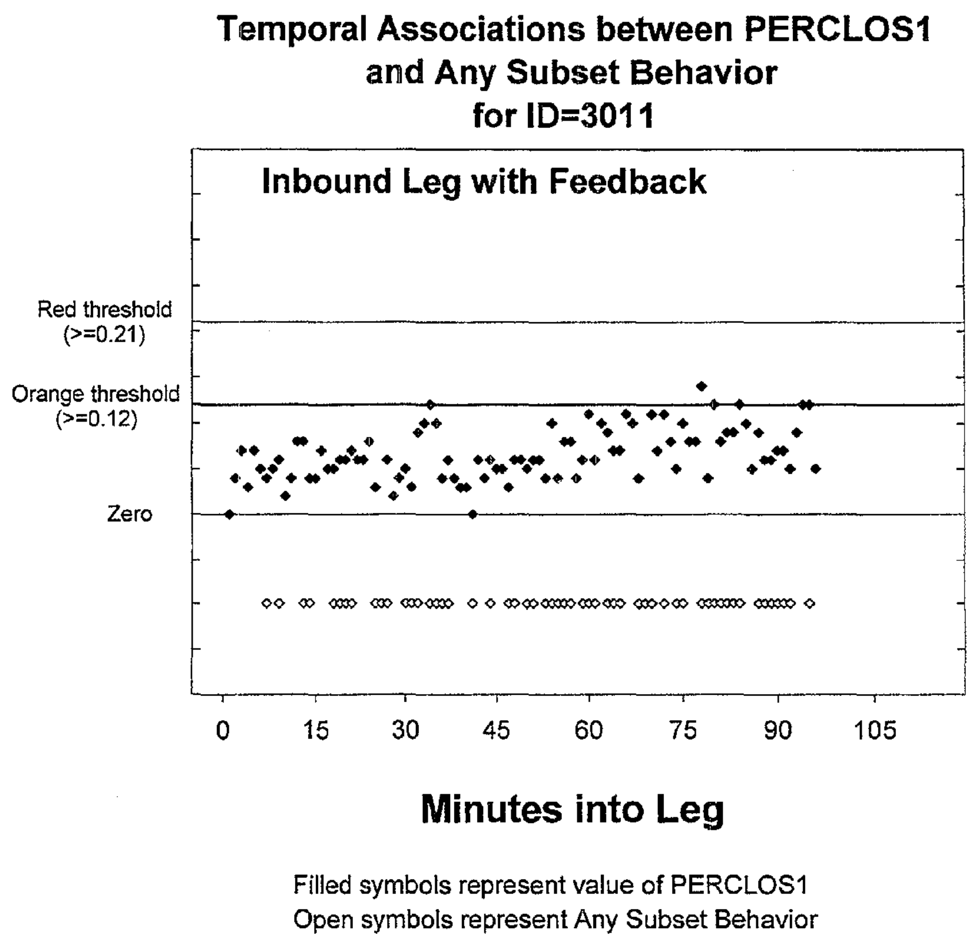

Figure 54. Temporal relationship for subject 3011 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the inbound leg of the nighttime drive in which PERCLOS feedback was provided.

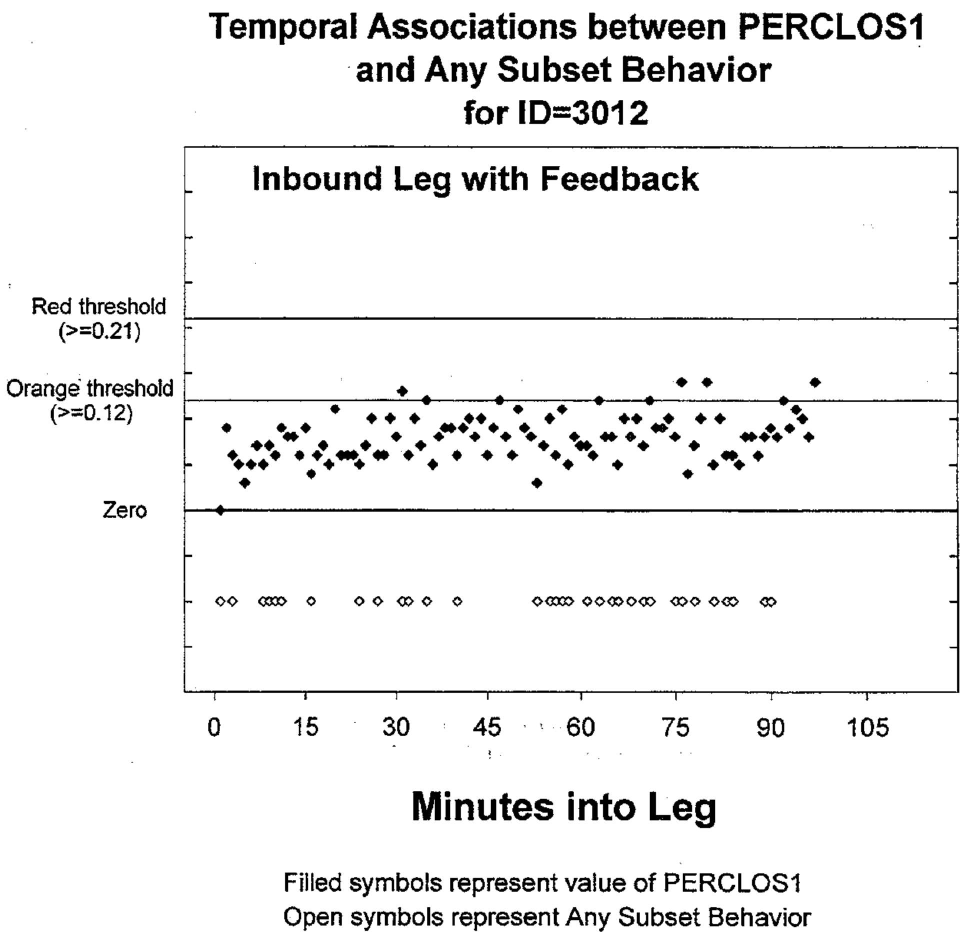

Figure 55. Temporal relationship for subject 3012 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the inbound leg of the nighttime drive in which PERCLOS feedback was provided.

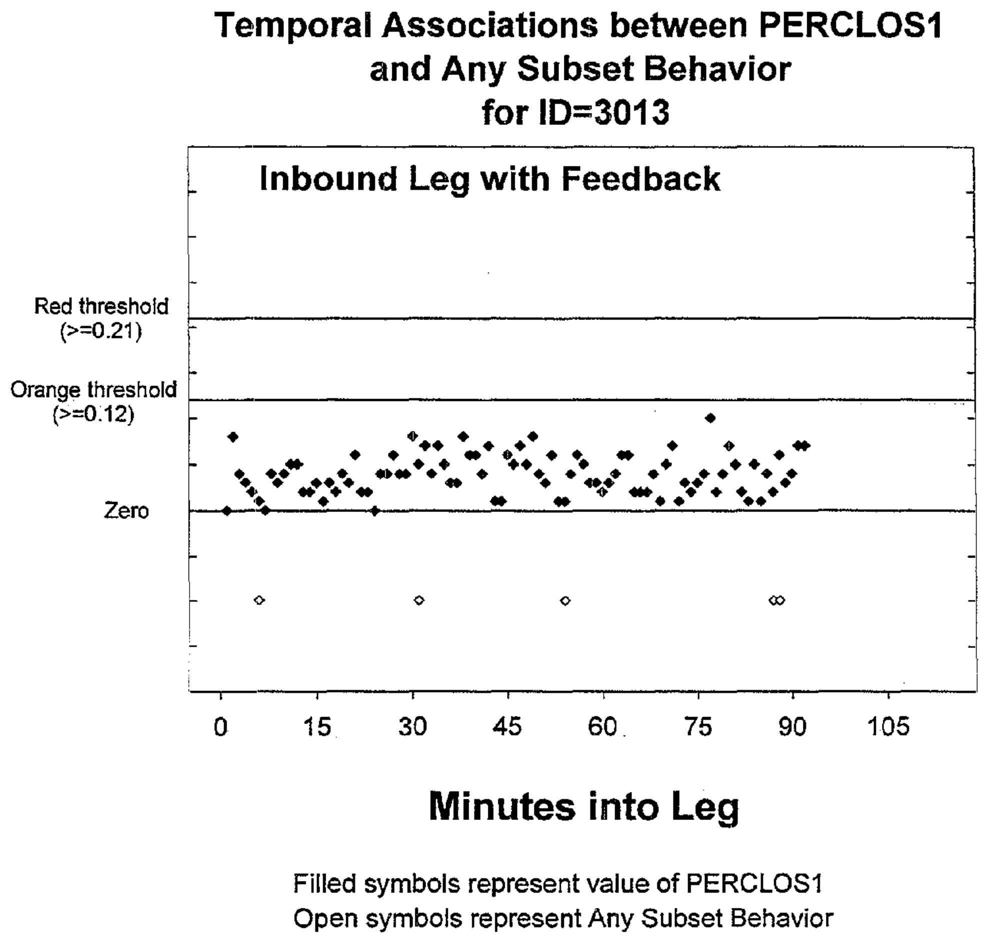

Figure 56. Temporal relationship for subject 3013 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the inbound leg of the nighttime drive in which PERCLOS feedback was provided.

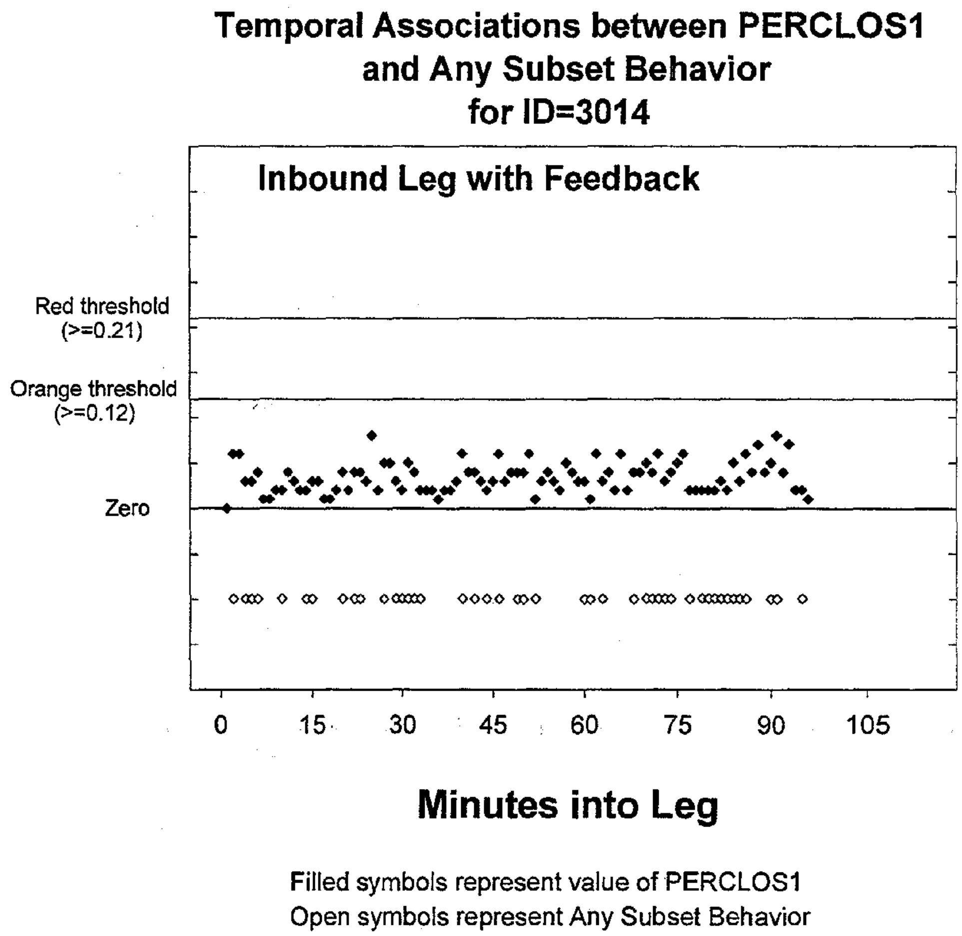

Figure 57. Temporal relationship for subject 3014 of 1 minute PERCLOS values and subset behaviors consisting of any combination of postural changes, rubbing face, rubbing neck, and stretching during the inbound leg of the nighttime drive in which PERCLOS feedback was provided.

REFERENCES

ATAF/FHWA/NHTSA: *Technical Conference on Enhancing Commercial Motor Vehicle Driver Vigilance*, Proceedings of a conference organized by the American Trucking Associations Foundation in cooperation with the Federal Highway Administration and the National Highway Traffic Safety Administration Transportation Safety Associates, pp. 1-87, December 10-11, 1996.

Diggle PJ, Liang K-Y, Zeger SL: *Analysis of longitudinal data*, Oxford: Claredon Press, pp. 64-68, 1996.

Dinges, DF, Pack, F, Williams, K, Gillen, KA, Powell, JW, Ott, GE, Aptowicz, C, Pack, AI: Cumulative sleepiness, mood disturbance, and psychomotor vigilance performance decrements during a week of sleep restricted to 4-5 hours per night. *Sleep 20(4)*:267-277, 1997.

Dinges, D.F., Mallis, M.M.: Managing fatigue by drowsiness detection: Can technological promises be realized? In Hartley, L. (Ed) *Managing Fatigue in Transportation*. Pergamon, Oxford, 1998, pp. 209-229.

Dinges, D.F., Mallis, M., Maislin, G., Powell, J.W.: Evaluation of techniques for ocular measurement as an index of fatigue and as the basis for alertness management. U.S. Department of Transportation,104pp, *Report No. DOT HS 808 762*, 1998.

Feldman H.A. Families of lines: random effects linear regression analysis, *J. Appl. Physiol.* 64(4):1721-1732, 1988.

Gibbons R.D., Hedeker D., Waternaux C. and Davis J.M. Random regression models: A comprehensive approach to the analysis of longitudinal psychiatric data", *Psychopharmacology Bulletin* 24:3:438-443, 1988.

Grace, R., Byrne, V. E, Bierman, D. M., Legrand, J. M., Gricourt, D. J., Davis, R.K., Staszewski, J. J., Carnahan, B., "A Drowsy Driver Detection System for Heavy Vehicles," proceedings Ocular Measures of driver Alertness Conference, Herndon VA, April 27 - 28, 1999.

Grace, R., Guzman, A.M., Staszewski, J.J., Peters, B.A., Mallis, M.M., Dinges, D.F., The Carnegie Mellon Truck Simulator, A Tool to Improve Driving Safety. *Proceedings of the SAE International Truck & Bus Meeting and Exposition*, November 16-18, 1998.

Kennedy, R.S., Lane, N.E., Berbaum, K.S., and Lilienthal, M.G.:Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *International Journal of Aviation Psychology*, 3, 203-220, 1993.

Mallis, M.M., Maislin, G., Powell, J.W., Staszewski, J.J., Grace, R., Dinges, D.F.: New drowsiness detection technologies: Testing their validity to track hypovigilance. *Sleep* 21(3): 242, 1998.

Proc Mixed, SAS/STAT Software: Changes and Enhancements through Release 6.12, Cary: SAS Institute, pp. 571-701, 1997.

Wierwille, WW, Ellsworth, LA, Wreggit, SS, Fairbanks, RJ, Kirn, CL: Research on vehicle-based driver status/performance monitoring: development, validation, and refinement of algorithms for detection of driver drowsiness. *National Highway Traffic Safety Administration Final Report: DOT HS 808 247*, 1994.

Wierwille, W. W., Lewin, L.G., Fairbanks, J, R. "Research On Vehicle-Based Driver Sataus/Performance Monitoring, Part III",DOT HS 808 640, September 1996.