A DROWSY DRIVER DETECTION SYSTEM FOR HEAVY VEHICLES

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Abstract

Driver drowsiness/fatigue is an important cause of combination-unit truck crashes. Drowsy driver detection methods can form the basis of a system to potentially reduce accidents related to drowsy driving. We report on efforts performed at the Carnegie Mellon Driving Research Center to develop such in-vehicle driver monitoring systems. Commercial motor vehicle truck drivers were studied in actual fleet operations. The drivers operated vehicles that were equipped to measure vehicle performance and driver psychophysiological data. Based on this work, two drowsiness detection methods are being considered. The first is a video-based system that measures PERCLOS, a scientifically supported measure of drowsiness associated with slow eye closure. The second detection method is based on a model to estimate PERCLOS based on vehicle performance data. A non-parametric (neural network) model was used to estimate PERCLOS using measures associated with lane keeping, steering wheel movements and lateral acceleration of the vehicle.

Introduction to the Drowsy Driver Problem

There are approximately 1.6 million truck tractors and 3.6 million trailers used in the motor carrier industry today. Advanced technology offers a significant potential to improve the productivity of the industry and help reduce the approximately 200,000 crashes in which combination-unit trucks are involved each year.

Driver drowsiness/fatigue is an important cause of combination-unit truck crashes. Recent analyses of the problem estimate that 1,200 deaths and 76,000 injuries can be attributed to fatigue related crashes annually.[1] The cost of these crashes is an estimated $12.4 billion per year and $2,060 per vehicle over the lifetime of a combination-unit truck.[2] This toll motivates efforts to identify and implement effective countermeasures for driver fatigue.

[1] Rau, P. S. (1996). NHTSA's drowsy driver research program fact sheet. Washington, D. C.: National Highway Traffic Safety Administration.
[2] Wang, J. S., Knipling, R. R., and Blincoe, L. J. (1996). Motor vehicle crash involvements: a multi-dimensional problem size assessment. Sixth Annual Meeting of the American Intelligent Traffic System, Houston, TX April 14-18, 1996. Washington, D. C.: National Highway.

We report on efforts performed at the Carnegie Mellon Research Institute (CMRI) Driving Research Center (DRC) to develop such countermeasures. The objective of this work is to devise and develop an in-vehicle system for Commercial Motor Vehicles designed to continuously monitor drivers for drowsiness. If it is possible to detect when a driver is drowsy and may fall asleep behind the wheel, it may be possible to implement accident prevention countermeasures.

Psychophysiological measures (e.g., devices to detect slow eye closure) and driver performance (e.g., steering wheel movements, lateral lane position, longitudinal speed, lateral and/or longitudinal acceleration, braking) are both classes of measures that could provide information to contribute to drowsiness detection. Vehicle based systems and psychophysiological systems can be applied separately or in combination to enhance system robustness. Both a video-based system to measure eye closure and driver performance-based detection methods are currently under consideration at the Carnegie Mellon DRC.

The development of a special camera system intended to obtain psychophysiological measure of eye closure is the main focus of this paper. First, there will be a discussion of the foundation of this eye-closure-based drowsiness detection system work, followed by detailed account of the Perclos camera development. Next, the other work based on driver performance measures will briefly be mentioned in order to provide insight into an alternative approach to drowsiness detection. A summary of the progress made at the DRC will be included along with future work intended to move closer to the DRC goal of developing an in-vehicle system for Commercial Motor Vehicles to continuously monitor drivers for drowsiness.

Fundamental Principles of a Video-Based Drowsiness Detection System

A special video-based system is under development at CMRI that measures eye closure, more specifically, PERCLOS. PERCLOS is defined as the proportion of time the eyes are closed 80% or more for a specified time interval.[3] Recent results from efforts at the DRC[4] and the University of Pennsylvania[5] have shown that ocular measures of drowsiness, in particular PERCLOS, can be effective in identifying lapses in attention due to drowsiness and that PERCLOS can be measured directly using video processing techniques. Significant progress has been made in fielding a device that directly measures PERCLOS in real time.

Field Study

Data collected from the DRC field study (see footnote 4) involving truck drivers driving their normal evening/early morning hour shift over a two week period provided a foundation for the work discussed here. Duty periods covering a 7 pm to 7 am time interval were selected to maximize the frequency with which drowsy episodes were likely to occur and to observe drivers when they were likely to pose the greatest threat to safety.

On-road data collection involved professional commercial motor vehicle drivers driving vehicles identical to those used by their firm, but specially instrumented to collect vehicle performance and psychophysiological

[3] Weirwille, W.W. (1994). "Overview of Research on Driver Drowsiness Definition and Driver Drowsiness Detection," 14th International Technical Conference on Enhanced Safety of Vehicles (ESV), Munich, Germany, May 23-26.
[4] Grace, R., Staszewski, J.J., Byrne,V.E., Davis R.K., Bierman, D. M., Jarrett, J., Swecker, G.W. (1998) "Develop, Test, and Evaluate a Drowsy Driver Detection and Warning System for Commercial Motor Vehicles, Draft Final Report," submitted to US DOT.
[5] Dinges, D. F., Mallis, M.M., Maislin, G., Powell, J.W. (1998) "Evaluation of Techniques for Ocular Measurement as an Index of Fatigue and as the Basis for Alertness Management, Draft Final Report," submitted to US DOT.

measures as unobtrusively as possible. Instrumentation consisted of a video camera and recording system for capturing drivers' faces and sensors for collecting drivers' head positions. Also recorded were steering wheel movements, the vehicles' lateral acceleration, and the vehicles' position relative to roadway lane boundaries.

Approximately 500 hours of recorded video images were collected. The video tapes were monochromatic and through the use of 880 nanometer light source, a pronounced retinal reflection resulted making the eyes appear to glow.

Specially trained coders were employed to manually generate ocular measures of drowsiness from the video tape records using previously developed techniques for measuring PERCLOS (see footnote 3). The coder's task involved estimating the degree to which a driver's eyes were open or closed. From this data, PERCLOS was extracted. The reliability of the manual coders was assessed to be sufficient.

Based on the manual coding of PERCLOS, the field study was successful in capturing several drowsy episodes from overnight drivers. Two of the seven participating drivers showed frequent and severe bouts of drowsiness. Figures 1 and 2 show a typical night of observed drowsiness for these two drivers. Each plot spans the portion of the night's run where the bout was observed (time is indicated on the horizontal axis), and the peaks and troughs of the plot itself represent the proportion of time PERCLOS was 80% or greater within each minute. Therefore, a value of 0.5 on the plot indicates that the driver's eyes were scored at least 80% closed for half of that paritcular minute.

The manual coding provided information about the number, duration, and severity of drowsy episodes amongst the drivers, however it is impractical and costly to consider placing a human in the cab of a truck to monitor drivers. Nevertheless, the information gained from the manual coders served as a baseline of comparison for automated systems currently under development.

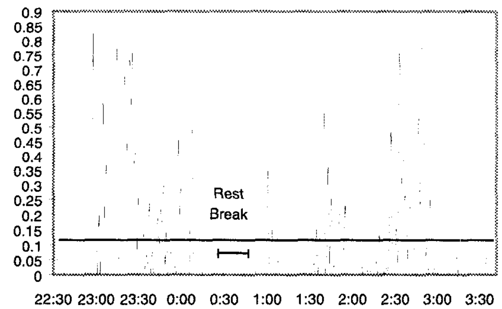


Figure 1: One night of observed drowsiness for Driver A.

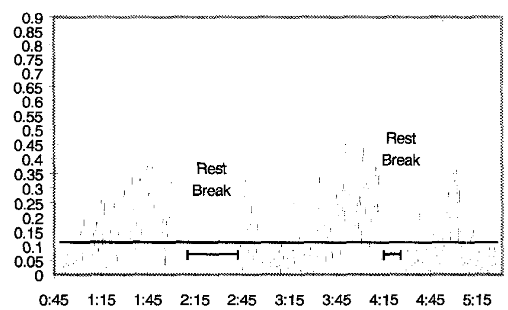


Figure 2: One night of observed drowsiness for Driver B.

Semi-automated Eye Tracking System

As a move towards more economically efficient measurement of eyelid closure, a semi-automated eye tracking system was developed. Some of the eye tracking procedures developed in this semi-automated system provided the necessary groundwork for the fully automated PERCLOS camera that was to follow.

The system tracked both eyes directly from a digitized video image, and independently calculated the percentage eye closure for each eye based on a pixel count. The system provided an eye closure value based on the eye that was most open.

The most important result to come out of testing the semi-automated eye tracking system was the system's ability to track the eyes with minimal operator intervention at a maximum rate of 6 frames per second. Through the course of testing, the system correlated very highly with manually coded data, and almost perfectly with itself on repeated trials.

However, the most significant problem with the semi-automated eye tracking system was its tendency to lose the eye under various circumstances (thereby necessitating operator intervention). Specifically, large-scale head movements would often take the eyes outside of the algorithm's search space, rendering them lost. Competing bright spots near the eyes (due either to additional infra-red reflections other than the eye itself, or in some cases, ambient light) would sometimes cause the system to fail. In particular, images of drivers with eyeglasses could not be processed by the system because of the additional reflections created by the eyeglasses. The PERCLOS camera was able to eliminate many of these spurious reflections via a subtraction process (described later). Large-scale head movements did not present a problem to the PERCLOS Camera because of its altogether different method of frame handling (described later).

Also, significant speed improvements were realized with the PERCLOS camera, as it processed information via dedicated hardware, an utilized more refined data handling techniques.

Through the development, testing, and analysis of the semi-automated eye tracking system, several key elements were decided upon as critical to the success of the PERCLOS camera. First and foremost, the PERCLOS camera must be able to accurately measure eye closure in real time and for all drivers. In addition, the camera must sit stably in the cab of the truck, and yet be inconspicuous enough so as not to be a distraction or to hinder the driver's vision in any way. Finally, the camera must possess sufficient memory to be able to store an entire run's worth of data.

PERCLOS Camera

Overview

DRC has designed a prototype of the PERCLOS camera for measuring eye closure in a heavy truck environment. The prototype eye tracking system was designed using charge-coupled device (CCD) imaging technology and a dedicated PC/104 with PCI Bus computer platform. The system is currently capable of measuring driver eye closure under low-light conditions, and calculating the resulting PERCLOS values in real time.

Prototype

The PERCLOS camera works by exploiting a basic physiological property of the human eye: That the retina reflects different amounts of infra-red light at different frequencies. At the 850 nanometer wavelength (nm), the retina reflects 90-percent of the incident light. However, at 950nm, the retina reflects only 40-percent of the incident light. In order for the camera to work, it requires two equally illuminated images of the driver's face—one created with 850nm light, and one created with 950nm light. The only difference in the two images is the intensity of the retinal reflections, so when the second image is subtracted from the first, only the retinal reflections remain. Once isolated, the retinal image sizes are measured, and the results are used to calculate PERCLOS. This process is repeated ten times per second.

In order to get two identical images with different sources of light, the system utilizes two separate cameras, both focused on the same point, yet situated at a 90-degree angle to one another. The image is passed through a beam splitter which reflects the image onto the lenses of both cameras. In order to isolate the correct wavelengths of light, one camera is outfitted with an 850nm filter, and one with a 950nm filter. The result is two cameras which receive identical signals at the same point in time, but which filter only the specific wavelengths of light necessary for the subtraction process.

Technical Components

Listed below is a list of the required instrumentation and computer hardware for the camera prototype:

Instrumentation box components

- 2 CCD cameras
- 2 filters (850 and 950 nm)
- 1 beam splitter
- a fan to reduce heat from the infra-red source
- a board built to synchronize the 2 cameras and control the current of the LEDs
- 1 LED ring with 850nm and 950 nm LEDs

Hardware components

- 1 timing controller
- 2 frame grabbers
- a PC104 w/ PCI Bus and a PCMCIA hard disk to store data

A diagram of the PERCLOS Camera, its instrumentation and hardware, is given below (Figures 3 and 4):

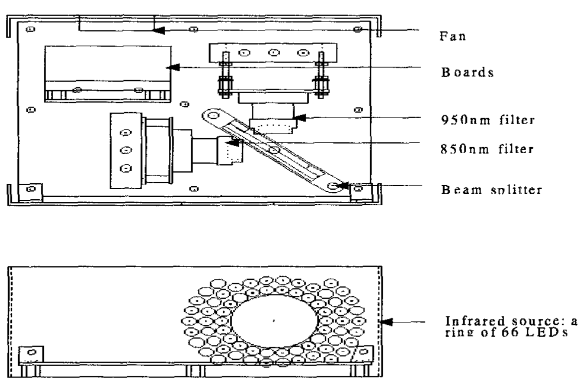


Figure 3: Instrumentation of PERCLOS Camera

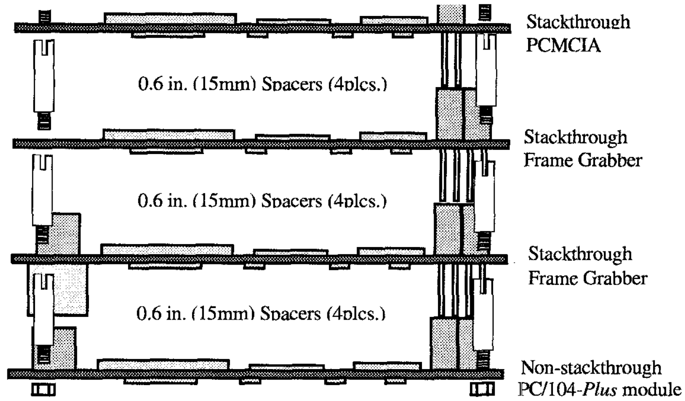


Figure 4: Hardware (PC/104 Stack) for PERCLOS Camera

Because the camera is being designed to fit in the cab of a commercial motor vehicle, there are several important considerations to make with respect to its portability:

- Size and weight - System must be small enough and light enough to fit unobtrusively in cab.
- Power consumption - System must have sufficiently low power consumption. Since power consumption is directly proportional to heat generation, reduced power consumption may be required to support operation in high ambient temperatures.
- Shock and vibration - System must be able to withstand a wide range of motion-induced stress for an extended period of time.
- Temperature and humidity - System must be able to withstand large fluctuations in ambient temperature and humidity.
- Electrostatic and electromagnetic interference - System must be protected from possible interference emitted from radio/radar signals in the vicinity, as well as from other electrical devices in the truck.
- Power supply irregularities - System must be able to withstand possible fluctuations in its power current caused by irregularities in vehicle power sources (e.g. starting of the engine)
- Maintenance and repair - System must have a high mean time between failure (MBTF) rate.

Knowledge gained from the laboratory semi-automated eye tracking system was used to design and construct this rugged version of the automated PERCLOS camera system for field-testing.

The System's Algorithm

The process by which the PERCLOS camera reads in video images and processes the images to generate eye closure values involves eight steps:

1. Initialization - Prior to calling any program routines, the system must be initialized. Among the processes carried out during initialization are: 1) Determining which frame grabber is which and assigning them to their corresponding PCI bus slots, and 2) Setting the correct image size, thereby saving memory and bandwidth for later use.

2. Frame Grabbing - The frame grabbing process stores in memory the images captured by each camera. It operates on a simple loop which 1) grabs a frame from the video stream, and 2) processes the information in it.

3. Image Synchronization - The synchronization routine ensures that the frames being processed from each camera line up perfectly. This is necessary in order to guarantee that the correct images are being subtracted from one another.

4. Subtraction - The subtraction process is the principal routine in the system. Essentially, it is a very simple, computationally-inexpensive routine, which subtracts each value in the 950-image buffer from each value in the 850-image buffer, and stores the result in a subtraction buffer.

5. Bright-Spot Segregation - The bright-spot segregation routine clusters all regions in the subtraction buffer which contain non-zero pixel values. The routine first gathers all the bright pixels contained within a certain area, and then passes the values contained in each cluster to the extraction routine which determines whether the cluster is an eye, or noise.

6. Eye Extraction - The eye extraction routine discriminates the eye from surrounding noise. It does this by summing the pixel values of each cluster, and choosing the two largest clusters above a certain threshold to make the eye/noise distinction. While the summing process is computationally inexpensive and quite fast, it isn't 100% accurate. For this reason, an additional process is carried out which calculates the correlation between each candidate cluster and an "ideal" eye. The two highest scoring clusters are chosen as the eyes, and all other clusters are discarded.

7. Eye Measurement - The eye measurement routine calculates the height (i.e. degree of openness) of each eye, and chooses the larger of the two values for storage.

8. Data Storage - The data storage routine stores the time and the calculated height of each observation in a data file on the PCMCIA hard disk.

Screen captures illustrating the 850nm image, the 950nm image, and the subtracted image are shown below (Figures 5, 6, 7):

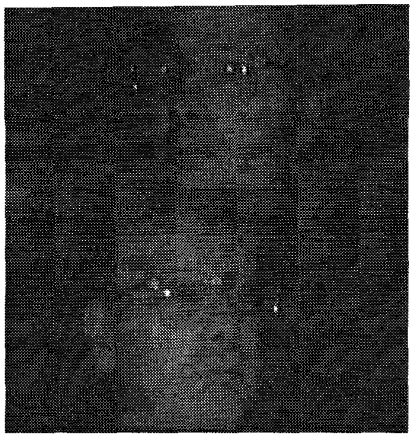
Challenges Met with Current PERCLOS Camera

The PERCLOS camera prototype solved many of the problems encountered with the semi-automated eye tracking system. Most significantly, it can run in real time without operator intervention. Additionally, eye recognition was greatly improved by correlating shape information with bright spot information. Also, the glare from drivers wearing glasses was eliminated completely with the subtraction process.

Figure 5: The 850nm image

Figure 6: The 950nm image

Figure 7: The subtracted image



Perclos Camera Placement into Heavy Trucks as a Detection System

The field test device is designed to operate under harsh conditions of vibration and electrical noise found in the environment of a typical tractor trailer cab. The device has recently been completed and has been installed for initial field-testing.

The initial field-testing will involve data collection during truck runs with selected drivers, laboratory analysis of the collected data, and making software refinements to optimize the accuracy of the PERCLOS measurements.

Future Directions in PERCLOS Camera Development

While the prototype of the PERCLOS Camera satisfies the requirement of a real time eye tracking system, there are changes that could be made to improve the system's operation and efficiency. Specifically, there are four changes that are scheduled to be made to the next generation PERCLOS Camera eye tracking system:

1. There will be a shift from a CCD image sensor to a complementary metal oxide semiconductor (CMOS) image sensor. The CMOS will not only provide greater sensitivity in the near infrared light spectrum, but it will also provide improved timing control, eliminating the problems with synchronization experienced in the prototype.

2. The PC104 microcomputer will be replaced with a microcontroller. This will eliminate the need for the frame grabbers as it will make the unit entirely self contained.

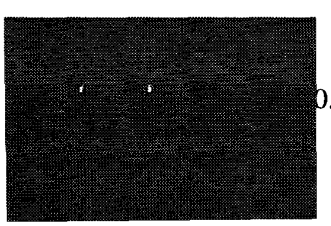
3. In order to allow more radiant energy while the image is captured, the system will pulse the LEDs. The pulsing will provide a higher signal-to-noise ratio, which will ultimately improve the system's ability to extract the eyes, and lower the system's total power consumption in the process. This will also serve to reduce the amount of infra-red light going to the eye.

4. The final change will involve redesigning the optics. A single lens will be placed in front of the filtering mechanism which will allow for the reduction in size of the optical set up.

An Alternative Approach to Drowsiness Detection – The Driver Performance-Based Model

Another approach to drowsiness detection that could be used in place of, or in conjunction with, the psychophysiological measure of eye closure involves the estimation of PERCLOS based on measurements of driver performance. Examples of driver performance measures include: Steering wheel movements, lateral lane position information, longitudinal speed, lateral and/or longitudinal acceleration, and vehicle braking. The categories of driver performance variables used in the CMRI DRC study (see footnote 4) included: Steering-related measures; lane-related measures; accelerometer-related measures; and head-position-related measures. Altogether, these measures provide a complete record of the driver's performance throughout the course of a run..

Results obtained from linear regression techniques indicated that seven variables were accounting for the majority of the variability



found in the PERCLOS measure. Therefore, it was these driver performance variables that were initially considered viable inputs to a performance-based drowsiness detection device. Specifically, the standard deviation of lane position, 4-steering wheel related measures, and 2-accelerometer related measures were isolated as the variables most contributing to the prediction of PERCLOS. It was this reduced set of variables that was then picked out for use with the neural networks. The neural networks are currently being developed and tested in order to determine the combination of driver performance variables that best model PERCLOS.

One potential drowsiness detection system might include both the video-based and driver performance- based systems to provide enhanced drowsiness detection specific to the habits and characteristics of individual drivers. Each approach provides its own set of costs and benefits, which should also be considered in future development.

Conclusions

The Carnegie Mellon DRC has put forth a considerable effort toward developing a video-based system to detect drowsiness in heavy vehicle truck operators. The work is firmly grounded in a field study also conducted at the DRC.

The current video-based system, the PERCLOS Camera, successfully measures eye closure in real time under nighttime driving conditions.

This ongoing research project is currently devoted to gathering field test data with the prototype system, improving and fine-tuning the system's performance, and further developing driver performance-based models of drowsiness detection.

Beyond the current efforts, the DRC also plans to begin exploring the various alerting/warning systems that could be triggered when drowsiness is detected.

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