

A REVIEW AND EVALUATION OF EMERGING DRIVER FATIGUE DETECTION MEASURES AND TECHNOLOGIES

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INTRODUCTION

The Federal Motor Carrier Safety Administration (FMCSA), the trucking industry, highway safety advocates, and transportation researchers have all identified driver drowsiness as a high priority commercial vehicle safety issue. Drowsiness affects mental alertness, decreasing an individual's ability to operate a vehicle safely and increasing the risk of human error that could lead to fatalities and injuries. Furthermore, it has been shown to slow reaction time, decreases awareness, and impairs judgment. Long hours behind the wheel in monotonous driving environments make truck drivers particularly prone to drowsy-driving crashes (1). Successfully addressing the issue of driver drowsiness in the commercial motor vehicle industry is a formidable and multi-faceted challenge. Operational requirements are diverse, and factors such as work schedules, duty times, rest periods, recovery opportunities, and response to customer needs can vary widely. In addition, the interaction of the principal physiological factors that underlie the formation of sleepiness, namely the homeostatic drive for sleep and circadian rhythms, are complex. While these challenges preclude a single, simple solution to the problem, there is reason to believe that driver drowsiness can nevertheless be effectively managed, thus resulting in a significant reduction in related risk and improved safety (2).

Addressing the need for a reduction in crashes related to driver drowsiness in transportation will require some innovative concepts and evolving methodologies. In-vehicle technological approaches, both available and emerging, have great potential as relevant and effective tools to address fatigue. Within any comprehensive and effective fatigue management program, an on-board device that monitors driver state in real time may have real value as a safety net. Sleepy drivers exhibit certain observable behaviors, including eye gaze, eyelid movement, pupil movement, head movement, and facial expression (3). Noninvasive techniques are currently being employed to assess a driver's alertness level through the visual observation of his/her physical condition using a remote camera and state-of-the-art technologies in computer vision. Recent progress in machine vision research and advances in computer hardware technologies have made it possible to measure head pose, eye gaze, and eyelid movement accurately and in real time using video cameras. In a conference sponsored by the U.S. Department of Transportation (DOT) on ocular measures of driver alertness, Wierwille (4)

identified computer vision as the most promising noninvasive, vehicle-based technology for monitoring driver alertness.

As a means of grouping such drowsiness detection technologies based on their similarities, Dinges and Mallis (5) proposed the following categories: readiness-to-perform and fitness-for-duty screeners; mathematical models/algorithms; vehicle-based driver performance measurements; and vehicle-based operator alertness/drowsiness/vigilance monitoring devices.

The focus of this paper is on the last category of alertness monitoring technologies. These technologies monitor – usually on-line and in real time – biobehavioral aspects of the operator; for example, eye gaze, eye closure, pupil occlusion, head position and movement, brain wave activity, and heart rate. To be practical and useful as driver warning systems, these devices must acquire, interpret, and feed back information to the operator in real world driving environments. As such, there exists a need and, thus, ongoing efforts are underway, to validate operator-based, on-board fatigue monitoring technologies in a real-world naturalistic driving environment. The objective of this paper is to review and discuss some of the activities currently underway to develop unobtrusive, in-vehicle, real-time drowsy driver detection and fatigue monitoring/alerting systems and to present a format by which these technologies may be evaluated for use in transportation operations.

The paper is therefore divided into three sections. The following section outlines the general scientific design guidelines for a practical, in-vehicle fatigue detection and monitoring system. Next, a proposed methodology that includes a number of criteria for evaluating user acceptance of such technologies is presented, and relevant implementation and design issues are highlighted. In the final section, an overview of several promising technologies that are currently in use or that will be available in the near future is provided, including technical features and a brief summary of the development status for each. As a means of comparing these technologies in light of the various scientific guidelines and user acceptance criteria that are discussed, the paper concludes with a tabular conceptualization of how one might approach such a task.

TECHNICAL AND DESIGN GUIDELINES

The guidelines and criteria used to assess the potential efficacy of the candidate alertness monitoring technologies and devices relate to the functional characteristics and operational properties of the device or technology. In most cases, this list lacks the technical details necessary to be considered a functional requirements specification. Nevertheless, addressing these general user acceptance and scientific criteria is vital to ensure that any proposed device or technology is qualified for its intended purpose of monitoring, unobtrusively and in real time, driver alertness and thereby, in theory, helping to mitigate motor vehicle crashes related to driver drowsiness. A list of possible implementation issues is also presented. Sources of information used to compile these requirements included Dinges and Mallis (5), Whitlock (6), and Bekiaris et al. (7).

Scientific/Engineering Guidelines

- The device should measure what it is intended to, operationally (e.g., eye blinks, heart rate, etc.) and conceptually (e.g., alertness).
- The device should monitor driver behavior in real time.
- The device should be consistent in its measurement over time, and it should measure the same event (operationally and conceptually) for all drivers.
- The device should be able to operate accurately and reliably in both daytime and nighttime illumination conditions.
- For devices that produce audible warnings, it should be possible to hear the auditory output under all driving conditions at a level that is not startling to the user. The volume of auditory output should be adjustable over a reasonable range, approximately 50dB to 90dB.
- The device should be able to operate accurately and reliably over the expected range of truck cab temperature, humidity, and vibration conditions.
- The device should be designed to maximize sensitivity and specificity. In other words, it should minimize missed events (false negatives) by accurately and reliably

- detecting a reduced alertness state, and it should minimize false alarms (false positives) by accurately and reliably identifying safe driving and operator vigilance.
- The device should be able to operate continually and robustly over time with only normal maintenance and replacement costs.

USER ACCEPTANCE ASSESSMENT METHODOLOGY

Regardless of the projected safety benefit for any given vehicle drowsy detection technology, successful deployment is unlikely if users do not deem the device acceptable. Past work in the area, including that of Dinges and Mallis (5), Whitlock (6), and Bekiaris et al. (7), has specified a number of criteria that should be considered when evaluating the user acceptance of such technologies. Building on and encompassing these efforts where practical, DOT has conceptualized a methodology to systematically assess user acceptance for the purposes of the evaluation of various new and emerging vehicle technologies. This methodology is largely based on the *NHTSA ITS Strategic Plan for 1997-2002* (8) and has evolved and been expanded iteratively for DOT projects involving field operational tests. In this approach, acceptance is dependent upon the degree to which a driver perceives the benefits derived from a system as greater than the costs. If a system's potential for safety is not perceived to outweigh its costs, it is likely that the system will not be purchased, or purchased but not utilized. On the other hand, if safety potential and driving skill enhancement as related to device use are perceived, then there is a chance that users will feel comfortable engaging in riskier driving behavior. It is important that each of these outcomes be assessed for a complete evaluation of the safety and user acceptance of such technologies. This may be accomplished conceptually by deconstructing user acceptance into five broad elements: *ease of use*, *ease of learning*, *perceived value*, *advocacy*, and *driver behavior*. Systematic evaluation of these areas includes the assessment of multiple criteria, each of which is based on human factors principles as applied to vehicle technologies.

Ease of use is one component of user acceptance for a vehicle safety device. This encompasses the degree to which drivers find a technology understandable, usable, and intuitive in its operation and maintenance. Full consideration should be given to the human factors design, usability, and maintenance of a device. Testing may initially take place in a laboratory

setting to ensure the accommodation of inherent variability in driver anthropometry, cognitive and physical capabilities, as well as proper operation within various driving environments. Further design and usability evaluation in the field and longitudinally will aid in refining the functionality of such technologies and assessing driver device use patterns over time. Additionally, given various device states, it is critical to determine the degree to which drivers understand the capabilities and limitations of a system, its operational parameters, and what driver actions are expected in assorted situations. The degree to which devices accommodate individual drivers by promoting correct interpretation of their output, assuming individual differences in perceptual, information processing, physical, and cognitive skills, must also be evaluated. Moreover, it is necessary to assess the demands of attending to the output of an in-vehicle device, as a safety technology should never contribute to driver stress or workload. As device feedback typically takes the form of an auditory warning or alert, it is vital that various outputs are easily comprehended, discriminated, and do not conflict with those provided by other safety technologies. Finally, in order to facilitate trust in the safety benefit of such devices, it is crucial that false and/or nuisance alarms are minimized, in addition to maximizing ‘hits’ (i.e., correct assessments of driver status).

Ease of learning as a part of evaluating user acceptance seeks information regarding how well a device is utilized in its intended manner, as well as what is done with such acquired knowledge over time. If a device is well designed, then its operation is congruent with a user’s mental model and therefore easily understood, recalled, and retained. Furthermore, device output should be both intuitive and easily comprehended. Basic testing of such parameters may be conducted in a simulated setting for the evaluation of short-term outcomes. However, only a longitudinal study in field conditions allows for the assessment of learning over time. User understanding of the applications of device feedback, both reactively and proactively, in the case of fatigue management planning, is critical for the success of such technologies.

The *perceived value* element of user acceptance assesses the degree to which drivers perceive a safer and/or more alert driving environment as a function of device use. Ideally, the driver is able to utilize such safety-enhancing technologies to facilitate alert vehicle operation, in conjunction with successfully integrating device feedback more broadly into a personal fatigue management program. An additional aspect of perceived value is the degree to which drivers report that these innovations enhance driving performance and safety on the road. When

assessing these criteria, it is important to also consider the undesirable outcome of drivers' inadvertent or purposeful over-reliance on such technologies to maintain alert and safe vehicle operation. Perceived value may also be impacted as a result of the degree to which drivers understand and are informed about device functioning and what aspects of driver behavior the device monitors. For example, if real or perceived health risks are associated with the technology, drivers will weigh such costs against other perceived benefits. Additionally, users may be concerned about data confidentiality to the extent that devices are used to monitor, store, and possibly transmit information regarding their driving behavior.

Advocacy is measured in terms of the extent to which drivers consider endorsing or purchasing a safety device, and it is a critical component of user acceptance. Ultimately, regardless of a potential safety benefit, and even in spite of perceived benefits on the part of the driver, if a technology is not attainable by the intended users, it will not succeed in the marketplace. Therefore, the willingness of drivers both to purchase a safety device (whether on an individual or commercial basis) and to endorse it to others is a vital aspect of successful deployment.

Finally, alterations in *driver behavior* may occur as a function of device usage over time. Ideally, these changes are intended, positive, and have a permanent impact on safe vehicle operation and driver lifestyle. Evaluating a driver's allocation of cognitive and temporal resources to maintain safe driving serves to ensure that driving behavior is not negatively affected by devices requiring excessive time and cognitive resources to monitor and react to. Of additional importance is assessing the degree to which driver awareness of and exposure to device feedback over time yields behavioral adaptation. Examples include the extent to which device output is integrated into driving behavior and the potential benefits and/or risks of using a technology in an unintended manner. Further, user acceptance should focus on alterations in driving style (i.e., habits, patterns) that are brought about by modifications to sleep/wake patterns as a result of responding to device output. More broadly, it is important to assess whether extended exposure to such safety devices leads to overall lifestyle changes with regard to fatigue management.

Implementation and Design Issues to Consider

A number of implementation and design issues should be taken into account for the successful implementation and practical use of a device. These implementation issues include:

- Human factors considerations for device controls and display design and location are critical when implementation in a vehicle cab environment is planned. The system should not obstruct the driver's view of the road scene, nor should it obstruct vehicle controls and displays required for the primary driving task. It should be designed such that allocation of driver attention to the system displays and controls remains compatible with the demand of the driving situation.
- Issues related to privacy of the data acquired by the device (i.e., who has access to data) must be considered, as drivers may be reluctant to voluntarily use a technology that is perceived as having the possibility for providing damaging information to outside parties regarding their driving.
- Acceptance or "buy-in" from stakeholders – drivers, fleet operators/managers, trucking associations, and labor unions – must be obtained.
- Issues related to automatic vs. manual activation and deactivation of the device must be considered.

SUMMARY AND ASSESSMENT OF FATIGUE DETECTION AND MONITORING TECHNOLOGIES

Technological approaches for detecting and monitoring dangerous levels of driver drowsiness continue to emerge and many are now in the development, validation testing, or early implementation stages. Previous studies have reviewed available drowsiness detection and prediction technologies and methodologies (9, 10). This paper builds on previous work by providing updated information on state-of-the-art emerging drowsiness detection and alertness monitoring technologies. Significant advances in video camera and computer processing technologies coupled with robust, non-invasive eye detection and tracking systems have made it possible to characterize and monitor a driver's state of alertness in real time under all types of driving conditions. In this section, some currently available drowsy driver monitoring devices, as well as technologies that will be available in the near future for commercial transport

applications, are identified and described. This information was compiled using a combination of several methods, including literature searches of technical/scientific journals and the Internet, e-mail and phone correspondence with researchers, engineers, and product managers involved in developing these technologies, and on-site visits and technical demonstrations. In each case, the information presented is categorized in terms of the device's background, functionality, and use; relevant research findings; and future directions for device development. It is also noted if no information was available to fit a particular heading.

Attention Technology, Inc.

Device Background, Functionality, and Use

Attention Technology, Inc. has designed and developed the DD850 Driver Fatigue Monitor (DFM), the only real-time, on-board drowsiness monitor that is currently being tested in an extensive field operational test. The DFM is a video-based drowsiness detection system for measuring slow eyelid closure. It is designed to mount on the vehicle's dashboard just to the right of the steering wheel, and it provides a continuous real-time measurement of eye position and eyelid closure (11, 12). The camera module is mounted on a rotating base to allow the driver to adjust the camera angle. The field of view is large enough to accommodate normal head movement. The device has a visual gauge that represents the driver's drowsiness level and emits an audible warning when the driver reaches a preset drowsiness threshold. With a three-stage alarm, the device provides real-time, immediate feedback to the driver.

Specifically, the DFM estimates PERCLOS, which is the proportion of time the eyes are closed 80% or more over a specified time interval. PERCLOS has been demonstrated in both driving and non-driving tasks to be a valid indicator of drowsiness and performance degradation due to drowsiness. In order to do this, the DFM uses a structured illumination approach to identify the driver's eyes (11). The bright pupil effect utilized by the DFM is a simple and effective eye tracking approach for pupil detection based on a differential lighting scheme. The high contrast between the pupils and the rest of the face can significantly improve the eye tracking robustness and accuracy. However, this technique also has disadvantages and limitations.

Research Findings

The success of the bright pupil technique strongly depends on the brightness and size of the pupils, which are often functions of face orientation, external illumination interference, and the distance of the subject from the camera (13). For real-world, in-vehicle applications, sunlight can interfere with IR illumination, reflections from eyeglasses can create confounding bright spots near the eyes, and sunglasses tend to disturb the IR light and make the pupils appear very weak. Thus, the DFM is intended for use in commercial operations involving nighttime driving.

An on-road field operational test (FOT) of the DFM, co-sponsored by FMCSA and the National Highway Traffic Safety Administration (NHTSA) is currently in progress to determine the safety benefits of using the device to measure the alertness of commercial truck drivers. The FOT consists of 37 vehicles equipped with the device and 102 truck drivers, each driving for 17 weeks.

Future Directions

None specified.

Delphi Electronics and Safety

Device Background, Functionality, and Use

Delphi is currently developing an automotive-grade, real-time, vision-based driver state monitoring system that aims to improve safety by preventing drivers from falling asleep or from being overly distracted. The system integrates two products, the ForeWarn Drowsy Driver Alert and the ForeWarn Driver Distraction Alert, into a comprehensive Driver State Monitor (DSM) (14). The DSM is a computer vision system that uses a single camera mounted on the dashboard directly in front of the driver and two IR illumination sources. Upon detecting and tracking the driver's facial features, the system analyzes eye closures and head pose to infer fatigue or distraction level. While Delphi considered drowsiness and distraction measures other than the ones based on computer vision (driving performance and heart/respiration rates, for example), computer vision was regarded as the preferred approach because it offers the most direct indication of early onset of sleepiness and distraction, and is also seen as an excellent platform to be shared with other vision-based driver assistance applications in the future.

The camera and IR illumination sources are unobtrusive, and the system provides an audible warning alert. The system also features automatic driver detection (self-calibration) and does not require training. The fatigue detection algorithm predicts AVECLOS, the percentage of time the eyes are estimated to be fully closed over a one-minute interval. This is a less complex measure of drowsiness than PERCLOS, and, as a result, it permits the use of an automotive-grade data processor as opposed to a high-grade PC processor required for PERCLOS. Validation testing at Delphi has shown very close correlation between AVECLOS and PERCLOS (Pearson correlation coefficient = 0.95).

Research Findings

DSM is being developed for the automobile and commercial vehicle market; thus, ensuring that the system works in a real-world automotive environment is critical. Some of the automotive requirements addressed during the design and development of DSM included a wide range of illumination conditions and operating temperatures, coverage of the 95th percentile ellipsoid of driver head positions, available camera locations, system cost, heat dissipation, allowable levels of IR irradiation, and subject variability. The production version of DSM will not have a display, though the current configuration being used for experimental testing and product development incorporates a display showing a video image of the driver's face/head and eye tracking region as well as color-coded outputs regarding levels of distraction and fatigue. The DSM is presently installed in a Volvo demonstration vehicle, where it has been shown to be a reliable predictor of drowsiness under all illumination conditions and for drivers wearing eyeglasses and most types of sunglasses.

Future Directions

None specified.

Seeing Machines

Device Background, Functionality, and Use

Seeing Machines faceLAB™ provides head and face tracking as well as eye, eyelid, and gaze tracking for human subjects using a non-contact, video-based sensor (15). FaceLAB™ has a flexible and mobile tracking system and a wide field of view that enables analysis of naturalistic behavior, including head pose, gaze direction, and eyelid closure, in real time under

real-world conditions without the use of wires, magnets, or headgear. Thus, it is a tool that has great promise for analyzing driver behavior in simulators and test vehicles.

Drowsiness can be determined in real time with faceLAB's comprehensive blink analysis and PERCLOS assessment, including delivery of raw data on the details of eyelid behavior. Measurements are taken on eyelid position, rather than bright pupil or corneal occlusion. In addition, faceLAB™ allows each subject to be automatically calibrated, and the data are reusable in subsequent experiments.

Seeing Machines' faceLAB™ has been employed extensively as a PC-based research tool. It is installed in several driving simulators, including the National Advanced Driving Simulator at the University of Iowa and at the University of Minnesota, and it has been used in test track experiments at NHTSA's Vehicle Research Test Center. In addition, a single-camera system is installed on a Volvo Safety Truck demonstration vehicle.

Research Findings

FaceLAB™ operates and maintains tracking integrity through a range of lighting and movement conditions. It is not sensitive to sudden movement or obstruction, and it recovers immediately if a subject leaves the field of view. The device reportedly works in bright sunlight or at night, with subjects close to the camera or several feet away. It also works with or without contact lenses and with most eyeglasses. For example, if the subject is wearing sunglasses and his eyes cannot be seen, faceLAB™ can still find the head pose, eyes, and mouth, and can, according to Seeing Machines, continue to produce reliable data. The device reportedly works very well in the simulator environment.

Future Directions

Currently, Seeing Machines is developing a prototype in-vehicle system for Volkswagen that will include a warning alert feature and will be tested under real-world conditions. The prototype will be available in approximately one year.

Smart Eye AB

Device Background, Functionality, and Use

Smart Eye AB provides the general public, industry, and research institutions with computer vision based software that enables computers and machines to detect human face/head movement, eye movement, and gaze direction (16). Smart Eye has developed and tested Smart Eye Pro 3.0, a remote and unobtrusive sensor that measures face and eye movement for a variety of applications, including transportation safety research (drowsiness, alertness) and simulators.

Smart Eye Pro 3.0 is a machine vision system that estimates head pose using a simple and robust method based on tracking of individual facial features and a three-dimensional (3D) head model. The initial head model is generic and adapted to the user. Once the system runs in tracking mode, the 3D feature locations are determined from their previous locations and a motion model. If tracking is suddenly lost, a fast face detection procedure allows the system to quickly re-acquire the subject's face and resume tracking. While the face is being tracked, gaze direction and eyelid positions are determined by combining image edge information with 3D models of the eye and eyelids. Smart Eye manufactures the image-processing based sensor but does not develop an algorithm that monitors drowsiness.

Research Findings

Smart Eye Pro 3.0 is able to provide accurate eye tracking under all illumination conditions, from bright sunlight to complete darkness, by using an innovative active IR lighting approach that suppresses the effects of sunlight and shadows. It also reportedly works well for drivers who have low contrast eyes and who wear contact lenses, eyeglasses, and most types of sunglasses.

A system consisting of a single camera and PC-based processor is currently being tested in Europe by Volvo, Volkswagen, BMW, and all the European truck manufacturers. Smart Eye reports that they have been receiving very favorable reviews from these on-road field tests with regard to the system's ability to monitor the driver's eye and head movement and gaze direction in both sunlight and darkness as well as for drivers wearing eyeglasses.

Future Directions

Smart Eye's long-term plan is to go into serial production and have the device available as an option for the automobile market in three years.

SensoMotoric Instruments GmbH (SMI)

Device Background, Functionality, and Use

SMI, based in Berlin, Germany, is currently developing InSight™, an advanced, non-invasive, computer-vision based operator monitoring system that measures head position and orientation, gaze direction, eyelid opening, and pupil position and diameter (17, 18). It is a high-speed system that uses a sampling rate of 120 Hz for head pose and gaze measurement, 120 Hz for eyelid closure and blink measurement, and 60 Hz for combined gaze, head pose, and eyelid measurement. To determine a driver's state of alertness, InSight™ calculates PERCLOS. The system is purported to employ automatic and robust tracking algorithms that allow accurate driver state monitoring under all lighting conditions from sunlight to darkness. The system also features very simple and fast user calibration to accommodate multiple drivers.

The present InSight™ configuration is a PC-based system that uses one high-speed, dashboard-mounted camera and three sources of low-intensity controlled IR illumination. The system provides a comparatively large tracking range because it uses a small tracking area on the face (eye and nose features only) for measuring head/face position and orientation. Their system is suitable for 24-hour operation. It measures head position and orientation, eye position, and eyelid closure for a more refined prediction of PERCLOS, and subsequently driver drowsiness.

Research Findings

The eye closure measurement accuracy is 1 mm. As mentioned, InSight™ is currently a PC-based research platform, although extensive studies have been conducted with truck drivers and passenger cars. SMI has also conducted studies comparing simulator and on-road performance to detect drowsiness and micro-sleeps. They have been working with Volkswagen and BMW to test the device in the real-world driving environment.

Future Directions

SMI's plan is to partner with an OEM by the summer of 2005 to develop the technology into a production-quality, automotive-based drowsiness detection and monitoring system.

Applied Science Laboratories (ASL)

Device Background, Functionality, and Use

ASL has been designing and developing eye tracking systems and devices for over 30 years for applications in fields such as human factors and ergonomics, marketing research, psychology and cognition, and education and training. Their video based eye trackers utilize the pupil/corneal reflection technique for measuring eye movements (19). In most applications, ASL devices operate with a bright pupil image. They have found that the bright pupil image is less affected by eyelashes, light colored eyes, dark environments, contact lenses, eyeglasses, and distance from the camera. On the other hand, a disadvantage of the bright pupil technique is that it is not as robust in an outdoor environment since sunlight can interfere with infrared illumination. In those cases, ASL uses a specially enhanced dark pupil technique in which the optics are designed specifically for outdoor use and are robust even in bright sunlight.

Many of ASL's eye tracking devices for outdoor applications (including in-vehicle driving purposes) utilize a camera mounted on an adjustable, lightweight headband. These devices provide unrestricted freedom of movement and can accommodate all types of subjects including those wearing sunglasses, but nevertheless may be considered, rather obtrusive. ASL does, however, manufacture a remote, non-contacting eye tracking system better suited for in-vehicle, real time monitoring of driver alertness.

The ASL technology that is developed for in-vehicle transportation applications is primarily a PC-based research instrument. The camera-based system is non-invasive, but the computer must be present in the vehicle to process the data. Also, the eye tracking system does not include an algorithm for detecting and alerting a drowsy driver.

Research Findings

This system, the ETS-PC II, is designed to provide a full 90° horizontal and 45° vertical field of view for accurate measurement of the driver's eye movement and line of sight. The eye is reliably reacquired if the head is turned over 90° and then returns. Furthermore, the system can reportedly integrate eye gaze data with a time stamp to other data signals from the vehicle, such as steering position or vehicle speed. ASL states that the device works in all driving conditions from bright sunlight to total darkness.

Future Directions

None specified.

LC Technologies, Inc.

Device Background, Functionality, and Use

LC Technologies, Inc. has developed an eye tracking technology that is both an eye-operated computer for control and communication and a device for monitoring and recording eye motion and related eye data (20, 21). The technology, called the Eyegaze Analysis System, is a hands-off, unobtrusive, remote human-computer interface that can be used to track a user's gaze point or allow an operator to interact with their environment using only their eyes.

The Eyegaze Analysis System is a tool for measuring, recording, playing back, and analyzing what a person is doing with his eyes. It includes all the basic video equipment, computer hardware, and Eyegaze software necessary to develop and run custom eye tracking applications. Gaze direction is determined using the Pupil Center Corneal Reflection (PCCR) method. A small, low power, infrared light emitting diode (LED) located at the center of the camera lens illuminates the eye and provides a direct reflection off the cornea of the eye.

For its use as a drowsy driver detection and warning system, the Eyegaze System can be housed in the vehicle cab to warn and alert drivers when they are becoming drowsy and losing alertness on the road. The goal of the system is to monitor the driver's eye point-of-regard, saccadic and fixation activity, and percentage eyelid closure reliably, in real time, and under all anticipated driving conditions. Recent effort at LC Technologies has been directed toward developing the camera/sensor instrument, but no significant work has been done to advance the Eyegaze system for transportation applications.

Research Findings

In most cases, eye tracking works with eyeglasses and contact lenses since the calibration procedure accounts for the refractive properties of the lenses. However, eyeglasses tilted significantly downward, hard contact lenses, and sunglasses may cause problems for the device by reflecting the LED off the surface of the glass back into the camera. In addition, sunlight contains high levels of infrared light and obscures the lighting from the device's LED, degrading the image of the eye.

It has been tested in a real-world environment on their RV platform; however, the purpose of the test was to track the eye movements of the passenger who was attempting to operate a computer with the eyes only in a hands-free mode. The device has not been validated against any measures of driver drowsiness such as PERCLOS or eye gaze behavior. It reportedly works well in sunlight and for drivers who wear most types of sunglasses (reflective sunglasses present a problem).

Future Directions

None specified.

Johns Hopkins University Applied Physics Laboratory (APL)

Device Background, Functionality, and Use

APL is developing a small sensor system that will alert drivers when they are in danger of falling asleep at the wheel or experiencing some level of impairment from fatigue (22). The Drowsy Driver Detection System (DDDS) is a device containing a transceiver similar to those used in automatic door entry systems that operate at safe microwave frequency and power levels. It detects drowsiness prior to the driver falling asleep. It issues warnings that can begin as the driver becomes sleepy and intensify as the system detects increasing drowsiness. The system is non-invasive and it collects specific driver data under all conditions, including bright sunlight, through the use of a Doppler radar system. The technique can monitor and quantitatively measure the speed, frequency, and duration of eyelid closure, rate of heartbeat and respiration, and pulse rate by analyzing the Doppler components in the reflected signal.

Based on the relatively simple design of the system and the projected low cost of production, the device is expected to be cost-effective to use. This technology is appealing from the standpoint of its ability to unobtrusively monitor driver behavior under all types of driving conditions and for all drivers. However, the technology has not advanced beyond the basic research phase of development.

Research Findings

Testing of the APL device has shown good correlation between measurements obtained with the DDDS and those taken using the validated PERCLOS methodology. But it should be noted that these tests were performed on only one subject.

Future Directions

Substantial additional work to develop the algorithm, collect data in the laboratory on several experimental subjects, and correlate the device output to a validated measure of drowsiness such as PERCLOS is required before a prototype system will be ready for real-world testing.

Rensselaer Polytechnic University (RPI)

Device Background, Functionality, and Use

Researchers at RPI have developed a prototype computer vision system for monitoring driver vigilance (3, 23, 24). The main components of the system include a remotely located charge coupled device (CCD) video camera, a specially designed hardware system for real-time image acquisition and for controlling the illuminator and alarm system, and various computer vision algorithms for simultaneous, real-time non-intrusive monitoring of various visual bio-behaviors that typically characterize a driver's level of vigilance. Their system can simultaneously and unobtrusively monitor in real time several visual behaviors that typically characterize a person's level of alertness while driving. These visual cues include eyelid and gaze movement, pupil movement, head movement, and facial expression. The parameters computed from these visual cues are subsequently combined probabilistically using a Bayesian Networks model to form a composite index that can robustly, accurately, and consistently characterize a driver's alertness level.

Eye detection and tracking are accomplished using active near-infrared illumination to brighten the subject's face to produce the bright pupil effect. This ensures a high-quality image under varying real-world conditions, including poor illumination, daylight, and darkness, and it minimizes any interference with the subject's ability to drive. For implementation of their system in a vehicle, RPI proposes to use two miniature CCD cameras embedded on the dashboard. The first camera is a narrow-angle camera focused on the driver's eyes to monitor eyelid and gaze movements, and the second camera is a wide-angle camera aimed at the driver's head to track and monitor head movement and facial expression. There are several ocular measures to characterize eyelid movement, such as eye blink frequency, eye closure duration, eye closure speed, and PERCLOS.

The RPI computer vision system focuses on real-time computation of PERCLOS and AECS to characterize eye movement. While PERCLOS is purported to be the most valid ocular parameter for measuring driver drowsiness, studies at RPI indicate that the average eye closure speed (AECS) differs for drowsy versus alert subjects and is, therefore, also a potentially useful and valid indicator of driver drowsiness. In addition to measuring eyelid movement, RPI has developed methods for determining three-dimensional face (head) orientation, eye gaze estimation and tracking, and facial expression (e.g., mouth movement, yawning). All these measures are potentially valuable in detecting a driver's level of alertness and attention.

Research Findings

Experimental studies in a simulated (laboratory) environment under various illumination conditions using eight subjects (both in a rested, alert condition and in a sleep-deprived condition) of different genders, ages, and ethnic backgrounds were conducted to validate the drowsiness monitoring system. The validation consisted of two parts; the first involved the validation of the measurement accuracy of their computer vision techniques and the second assessed the validity of the parameters that were computed to characterize drowsiness. On the basis of these experimental results, it was concluded that this monitor system is reasonably robust, reliable, and accurate in characterizing and predicting human drowsiness.

Future Directions

RPI has conducted both basic research and algorithm development. Their technological approach and prototype are promising, but limited to the laboratory environment. To advance their technology to a workable, on-board, automotive-grade system, RPI would need to collaborate with an industry partner.

George Washington University (GWU)

Device Background, Functionality, and Use

Researchers at GWU's Center for Intelligent System Research are developing a method for detecting drowsiness in drivers based on an Artificial Neural Network (ANN) (25, 26). The ANN observes the steering angle patterns and classifies them into drowsy and non-drowsy driving intervals. Unlike other drowsiness detection systems that are based on measuring driver physical and/or physiological data (EEG data and eye movements, for example) and that require

obtrusive wires, cameras, monitors, or other devices attached to or aimed at the driver, the ANN method measures and analyzes vehicle performance output data only. Thus, because of the non-invasive nature of this method and because it is not dependent on environmental conditions such as ambient light, neural network technology is potentially a very practical method for in-vehicle 24-hour fatigue/drowsiness monitoring.

Steering wheel movements have been of particular interest in studies of driver alertness. Various researchers have shown that changes in steering activity, computed over fixed time intervals, are correlated with a driver's state of impairment. The hypothesized relationship between driver state of alertness and steering wheel position is that in an alert state, drivers make small amplitude movements of the steering wheel, corresponding to small adjustments in vehicle trajectory; in a drowsy state, on the other hand, these steering wheel movements become less precise and larger in amplitude, resulting in sharp changes in trajectory.

Research Findings

GWU researchers trained and tested the ANN by conducting a driving simulator experiment. Twelve drivers, each under different levels of sleep deprivation, were tested. Results showed that the ANN method detected drowsiness with an accuracy of 90%. On several occasions during the simulator experiment, drivers fell asleep while driving and crashed the vehicle. The ANN detected drowsy driving behavior before the crash occurred and generated a warning in all cases.

Future Directions

This technology is still in the early research stage of development. Based on the work completed thus far, researchers at GWU have identified and recommended the following areas for further research:

- Conduct further refining and validation of the algorithm,
- Capture individual driver's steering activity while drowsy,
- Conduct additional simulator experiments to validate the algorithm, test additional road conditions, and test a more diversified group of drivers,
- Test the ANN technology on the road in an instrumented vehicle, and refine the algorithm based on the road test data, and
- Conduct research on warning systems integrated with the detection system.

DEVICE COMPARISON TABLE

The framework presented in Table 1 provides a means of comparing and contrasting the various technologies described in this paper. As an example, the technologies are evaluated against a number of the major user acceptance and scientific/engineering criteria: a '✓' denotes that the device meets the criterion or guideline; a '×' signifies that the criterion is not met; and a '•' indicates that the criterion has not been scientifically evaluated and more data are needed.

Table 1. Technology Comparison and Criteria Evaluation

Scientific/ Engineering Guidelines	Criteria	Attention Technology Driver Fatigue Monitor	Delphi Driver State Monitor	Seeing Machines faceLAB™	SmartEye Pro 3.0	SMI InSight™
Environmental	Device should operate reliably and accurately in all illumination conditions	✗	•	•	•	•
	Device should operate over expected range of truck cab temperature, humidity, and vibration conditions	✓	✓	✓	✓	✓
Reliability	Device should be designed to minimize both missed events and false alarms	•	•	•	•	•
Anthropometric	Device should accommodate multiple drivers with minimal re-calibration	✓	✓	✓	✓	✓
Engineering Design	Device should be robust and require only normal maintenance and replacement	•	•	•	•	•
User Acceptance Elements						
Ease of Use	Device must not be invasive	✓	✓	✓	✓	✓
	Device must accommodate corrective eyeglasses and most types of sunglasses	✗	✓	✓	✓	✓
	Device should present a warning alert to the driver	✓	✓	✓	✓	✓
	Device must monitor driver behavior in real time	✓	✓	✓	✓	✓
	Device should require minimal training	✓	✓	✓	✓	✓
Ease of Learning	Assessment of the time it takes users to feel proficient with the device	•	•	•	•	•
	Assessment of user ability to retain and recall information regarding device functionality	•	•	•	•	•
Perceived Value	Device should provide feedback to driver regarding alertness level	✓	✓	•	•	•
	Is there a perceived safety benefit or increased risk associated with device use?	•	•	•	•	•
Advocacy	Assessment of user's intent to purchase device	•	•	•	•	•
	Willingness of user to recommend device use to others	•	•	•	•	•
Driver Behavior	Device must not distract the driver from driving task or from responding to other safety devices	✓	✓	✓	✓	✓
	Assessment of behavioral adaptation to the device over time	•	•	•	•	•

Table 1. Technology Comparison and Criteria Evaluation (continued)

Scientific/ Engineering Guidelines	Criteria	ASL ETS-PC II	LC Tech. Eyegaze Analysis System	Johns Hopkins APL DDDS	RPI Prototype Fatigue Monitor	GWU Artificial Neural Network
Environmental	Device should operate reliably and accurately in all illumination conditions	•	•	•	•	✓
	Device should operate over expected range of truck cab temperature, humidity, and vibration conditions	✓	✓	•	•	•
Reliability	Device should be designed to minimize both missed events and false alarms	•	•	•	•	•
Anthropometric	Device should accommodate multiple drivers with minimal re-calibration	•	•	•	✓	✓
Engineering Design	Device should be robust and require only normal maintenance and replacement	•	•	•	•	•
User Acceptance Elements						
Ease of Use	Device must not be invasive	✓	✓	✓	✓	✓
	Device must accommodate corrective eyeglasses and most types of sunglasses	•	•	•	•	✓
	Device should present a warning alert to the driver	✗	✗	✗	✓	✗
	Device must monitor driver behavior in real time	✓	✓	✓	✓	✓
	Device should require minimal training	✓	✓	✓	✓	✓
Ease of Learning	Assessment of the time it takes users to feel proficient with the device	•	•	•	•	•
	Assessment of user ability to retain and recall information regarding device functionality	•	•	•	•	•
Perceived Value	Device should provide feedback to driver regarding alertness level	✗	✗	•	✓	•
	Is there a perceived safety benefit or increased risk associated with device use?	•	•	•	•	•
Advocacy	Assessment of user's intent to purchase device	•	•	•	•	•
	Willingness of user to recommend device use to others	•	•	•	•	•
Driver Behavior	Device must not distract the driver from driving task or from responding to other safety devices	✓	✓	✓	✓	✓
	Assessment of behavioral adaptation to the device over time	•	•	•	•	•

CONCLUDING REMARKS

Driver drowsiness pose a major threat to highway safety, and the problem is particularly severe for commercial motor vehicle operators. Twenty-four hour operations, high annual mileage, exposure to challenging environmental conditions, and demanding work schedules all contribute to this serious safety issue. Monitoring the driver's state of drowsiness and vigilance and providing feedback on their condition so that they can take appropriate action is one crucial step in a series of preventive measures necessary to address this problem.

This paper attempts to present in a concise and summary fashion some of the scientific activities and technological approaches that are currently underway to address driver drowsiness as a critical safety issue. Several promising state-of-the-art devices and technologies were identified and evaluated against a set of proposed design guidelines. Technological advances in electronics, optics, sensory arrays, data acquisition systems, algorithm development, and machine vision have made the goal of providing unobtrusive, real time, affordable, 24-hour driver alertness monitoring capability a near-term reality. Considerable development effort is taking place to demonstrate the scientific validity and reliability of these technologies, and more work is required before they can be fully implemented as an integral component of an overall fatigue management program.

REFERENCES

1. Sullivan, J. J. Fighting Fatigue. *Public Roads*. Federal Highway Administration, U.S. Department of Transportation, Vol. 67, No. 2, September/October 2003.
2. Rosekind, M. R. Managing Fatigue in Transportation: No Magic Bullet. Hearing on Fatigue and Its Safety Effects on the Commercial Motor Vehicle and Railroad Industries. United States Senate, Committee on Commerce, Science and Transportation. September 16, 1998.
3. Ji, Q., Z. Zhu, and P. Lan. Real-Time Nonintrusive Monitoring and Prediction of Driver Fatigue. *IEEE Transactions on Vehicular Technology*, Vol. 53, No. 4, July 2004.
4. Wierwille, W. W. Desired Attributes of Drowsy Driver Monitoring and Candidate Technologies for Implementation. *Technical Conference Proceedings, Ocular Measures of Driver Alertness*. Herndon, VA. April 1999.
5. Dinges, D. F. and M. M. Mallis. Managing Fatigue by Drowsiness Detection: Can Technological Promises be Realised? *Managing Fatigue in Transportation*. Proceedings of the 3rd Fatigue in Transportation Conference. Fremantle, Western Australia. 1998.
6. Whitlock, A. *Driver Vigilance Devices: Systems Review*. Quintec Associates Limited, Surrey, United Kingdom. August 30, 2002. Retrieved from <http://www.rssb.co.uk/pdf/reports/research/>.
7. Bekiaris, E., S. Nikolaou, and A. Mousadakou. *Design Guidelines for Driver Drowsiness Detection and Avoidance*. System for effective Assessment of driver vigilance and Warning According to traffic risk Estimation (AWAKE) Deliverable 9.1. AWAKE Consortium. August 2004.
8. NHTSA, ITS Joint Program Office, "Report to Congress on the National Highway Traffic Safety Administration ITS Program, Program Progress During 1992-1996 and Strategic Plan for 1997-2002". U.S. Department of Transportation, Washington, DC, January, 1997.
9. Krueger, G. P. Technologies and Methods for Monitoring Driver Alertness and Detecting Driver Fatigue: A Review Applicable to Long Haul Truck Driving. Draft Report. American Transportation Research Institute. June 7, 2004.
10. Hartley, L., T. Horberry, N. Mabbott, and G. P. Krueger. *Review of Fatigue Detection and Prediction Technologies*. Melbourne, Victoria, Australia: National Road Transport Commission. ISBN: 0-642-54469-7. September 2000.
11. Grace, R. Drowsy Driver Monitor and Warning System. Paper retrieved from <http://www.attentiontechnology.com/docs/DrowsyDriverMonitor.pdf>.
12. Grace, R., V. E. Byrne, D. M. Bierman, J-M Legrand, D. Gricourt, E. France, R. K. Davis, J. J. Staszewski, and B. Carnahan. A Drowsy Driver Detection System for Heavy Vehicles. *Technical Conference Proceedings, Ocular Measures of Driver Alertness*. Herndon, VA. April 1999.
13. Liu, X., F. Xu, and K. Fujimura. Real-Time Eye Detection and Tracking for Driver Observation Under Various Light Conditions. Retrieved from http://gscrlig1.eng.ohio-state.edu/flxu/publications/papers/pedestrian_iv2002.pdf.
14. Kisananin, B. and G. J. Witt. Driver State Monitoring from DELPHI. Delphi Corporation white paper. Provided by Gerald J. Witt, April 2005.
15. Seeing Machines, faceLAB 4. Web site. <http://www.seeingmachies/facelab.htm>.
16. Smart Eye white paper. September 2004. Retrieved from <http://www.smarteye.se/smarteyepro3.html>

17. InSight™ product description. Provided via e-mail by Eberhard Schmidt, Product Manager, SensoMotoric Instruments, GmbH. May 2005.
18. Driver Monitoring: Status SMI InSight™. PowerPoint presentation, provided via e-mail by Eberhard Schmidt, Product Manager, SensoMotoric Instruments, GmbH. April 2005.
19. Applied Science Laboratories product information. Provided on CD-ROM by Virginia Salem, Customer Relations, Applied Science Laboratories. May 2005.
20. L. C. Technologies, Inc., Eyegaze Systems. Web site.
<http://www.eyegaze.com/INDEX.htm>. April 2005.
21. Cleveland, D. Unobtrusive Eyelid Closure and Visual Point of Regard Measurement System. *Technical Conference Proceedings, Ocular Measures of Driver Alertness*. Herndon, VA. April 1999.
22. Johns Hopkins University Applied Physics Laboratory. Microwave and Acoustic Detection of Drowsiness. Retrieved from
<http://www.jhuapl.edu/ott/technologies/technology/articles/P01471.asp>. March 2005.
23. Ji, Q., P. Lan, and C Looney. A Probabilistic Framework for Modeling and Real-Time Monitoring Human Fatigue. Retrieved from
http://www.ecse.rpi.edu/~qji/Fatigue/smc_paper.pdf. May 2005.
24. Ji, Q. and X. Yang. Real-Time Eye, Gaze, and Face Pose Tracking for Monitoring Driver Vigilance. *Real-Time Imaging*, Vol. 8, pp. 357-377. 2002.
25. Sayed, R., A. Eskandarian, and M. Oskard. Driver Drowsiness Detection Using Artificial Neural Networks. Paper No. 01-2113. 80th Annual Meeting, Transportation Research Board. Washington, DC. January 2001.
26. Eskandarian, A. and R. Sayed. Driving Simulator Experiment: Detecting Driver Fatigue by Monitoring Eye and Steering Activity. PowerPoint presentation, NDIA 3rd Annual Intelligent Vehicle Systems Symposium. Retrieved from
<http://proceedings.ndia.org/3570/session5/Eskandarian.ppt>. March 2005.