# Review of on-road driver fatigue monitoring devices

Ann Williamson and Tim Chamberlain

NSW Injury Risk Management Research Centre
University of New South Wales
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## Introduction

Increasingly, we are becoming aware that fatigue while driving may contribute to a significant proportion of the crashes occurring on NSW roads. Current statistics estimate that fatigue plays a significant role in around 20 percent of fatal crashes on NSW roads, however, many acknowledge that this is likely to be an underestimate of the involvement of fatigue since many crashes that are attributed to other causes may also involve fatigue as a contributing factor.

One of the major problems in dealing with the road safety impact of driver fatigue is the difficulty in detecting when drivers are experiencing fatigue and in particular when fatigue is likely to increase the incidence of crashes. Other road safety problems that emanate from changes in the drivers functional state such as alcohol or drugs can be detected relatively readily by measuring their content in the body. Fatigue measurement is a significant problem as there are few direct measures, with most measures of the outcomes of fatigue rather than of fatigue itself. Probably the only direct measure of fatigue involves self-reports of internal states, however there are a number of problems in using any self-report measure due to the influence of demand effects or motivational influences. Furthermore, there is some evidence that fatigue becomes increasingly difficult to detect as it becomes more pronounced and that the more tired we become, the more likely it is that we will underestimate the effects of fatigue on performance.

These characteristics of fatigue measurement present a real problem for road safety. We need to be able to detect when fatigue is occurring as a first step in managing the problem.

Over the last ten years, there has been an increasing interest in the development of fatigue detection devices, with some motor vehicle manufacturers including devices in their vehicles that are marketed as fatigue warning systems (e.g., Citroen). The problem of fatigue detection is being attacked using a range of different approaches. This paper is a brief review of the literature on fatigue detection devices including a discussion of the likely effectiveness of these devices for managing driver fatigue.

## Aim

The objective of this review is to assess the current status of research into fatigue performance and detection technology and to identify any pertinent issues.

## Method

The initial search for information on fatigue detection technology first searched the scientific literature including Medline, Embase, Transport, IEEE Xplore, and PsycINFO using the search terms, “driver monitoring and fatigue”. As it was expected that a reasonable amount of the literature would be in the commercial or ‘grey’ area of the literature searches of the web were also conducted using Google with the search terms “driver monitoring and fatigue”. In addition, a number of articles concerning known fatigue detection systems (e.g., ALVINN, MANIAC, DAISY, DriveCam, faceLAB) were sought in the IEEE Xplore database.

**Results**
A summary of the papers located is found in Table 1. This literature is organised in terms of the approach used to detect or control fatigue, the name of the device (if applicable), the developers and a brief description of the distinguishing features of the approach/device and its state of development.

The literature located can be divided on the basis of the main focus of the methodology purported to reflect fatigue-related changes. These methodological emphases include measures of:

- the driver's current state, especially relating to the eye and eyelid movements and physiological state changes;
- driver performance, with a focus on the vehicle's behaviour including lateral position and headway;
- a combination of the driver's current state and driver performance.

Additionally, a portion of the literature can be isolated on the basis of its focus on fatigue-related countermeasures; a range of generic driver assistance devices that incorporate a driver warning signal.

1. Changes in the current state of the driver
The bulk of the literature on detection of fatigue effects and the driver's current state has specifically focussed on changes and movements in the eye. This includes a range of devices that assess changes in the driver's direction of gaze, rate of blinking and actual eye closure. Almost all of these methodologies have only been developed in the laboratory or have had limited application on-road. The eye tracking methods all use the same basic technology that involves a combination of infra red light directed at the eye and the reflection of this light which is then captured by a video camera. Many of these techniques have problems with detecting the eye under low light conditions or when head movements are frequent.

Two methodologies stand out as having potential for real-world applications. The first is the PERCLOS (Percent Eye Closure) methodology, a video-based method that measures eye closure. One of the strengths of PERCLOS is that attempts have been made to establish its validity as a fatigue detection device. Dinges, Mallis, Maislin and Powell (1998) evaluated the system against a number of different performance measures. Satisfactory relationships were obtained between eye closure and lapses in attention, providing some convergent evidence – when a measure correlates with other tests believed to measure the same construct – of the system's ability to detect the current state of the driver. Furthermore, PERCLOS showed the clearest relationship with performance on a driving simulator compared to a number of other potential drowsiness detection devices including two electroencephalographic (EEG) algorithms, a head tracker device, and two wearable eye-blink monitors.

The original PERCLOS methodology involved video recording of the driver's eyes to be later scored by trained observers. This methodology has been independently automated, most notably by the commercial company, Seeing Machines, emanating from the collaboration between the Australian National University and Volvo. The approach used by Seeing Machines, called faceLAB, is different from most other measures of eye closure and gaze direction. This method has the apparent advantage of being able to cope with low light conditions, head movement and tracking of gaze direction while the driver is wearing sunglasses. The faceLAB methodology has been validated, in simulated driving situations, against the PERCLOS methodology (Longhurst, 2002).

Some groups have looked at the use of EEG as a method for detecting drowsiness. Most of these studies have used EEG to validate the existence of drowsiness when other measures are being evaluated rather than as a fatigue-detection measure (e.g., Rimini-Doering, Manstetten, Altmueller, Ladstaetter and Mahler, 2001; Svennson, 2004). For example, a study by Lal, Craig, Boord, Kirkup and Nguyan (2003) demonstrated substantial relationships between an EEG algorithm for detecting fatigue and drowsiness under simulated conditions. The biggest drawback associated with EEG as an on-road drowsiness detection device is the difficulty in obtaining recordings under natural driving conditions; making it a somewhat unrealistic option for the detection of fatigue.

One group of researchers has evaluated in the laboratory a number of measures of driver alertness including head position, eye gaze, pupillary change and blink rate (Heitmann, Guttkuhn, Aguirre, Trutschel & Moore, 2001). These studies have led to the conclusion that no single measure of alertness is sufficiently sensitive or reliable and that multiple measures need to be considered, if a robust method of fatigue detection is to be developed. Further research is needed, however, to determine the best way of combining driver current state and performance measures and parameters for the accurate detection of fatigue and drowsiness.

Overall, the measures of driver drowsiness based on physical changes in the eye are developing into a technology that could potentially be used on the road. These approaches have a fundamental problem, however, in that the changes being measured are likely to be occurring late in the process of fatigue. It is possible that the driver has been through a significant period of high crash risk due to lowered alertness before significant eye closure effects are able to be detected. As a tool for fatigue prevention therefore, they will be signalling late stage fatigue and sleepiness when there are relatively few options for recovery apart from a period of sleep. While this is likely to be useful for preventing road traffic crashes, if drivers respond appropriately (i.e., with sleep) to any warnings resulting from these measures, drivers may be more likely to resist responding due to the inconvenience of having to stop their vehicle for a period to sleep. Methodologies that provide earlier warning of increasing fatigue may be better indicators of increasing crash risk and may be more readily acceptable to drivers. There is a wider range of countermeasures to alert a driver who is encountering early stage fatigue so giving drivers more options to respond to the problem. These include changing to another activity by having a break, using socially acceptable psychostimulants such as coffee or other caffeinated beverages or having a short nap. As drivers get more tired, the options to overcome the problem become reduced as such high levels of fatigue can only be overcome by a substantial period of sleep.

Other problems associated with the eye- and face-change detection technologies, are deciding on the point at which the driver is in an unsafe state and when a warning should be applied, and deciding on the nature of the warning signal itself. Some methods (e.g., PERCLOS, Parmar and Hiscocks, 2002; Veeraraghavan & Papanikolpoulos, 2001) discussed in the literature specify a period of eye closure, for example, at which a warning is triggered, however this method does not appear to have been based on any systematic evidence.

2. Driver performance measures

Most of the studies looking at on-road driver performance have employed lane tracking alone or in combination with tracking of the distance between the driver's vehicle and the car in front (or headway tracking). One of the major problems for these approaches is developing a system that can cope with large changes in the characteristics of the roadway, road quality and lighting. The most well developed of theses technologies, located in this review, was developed by a group at the Australian National University (Fletcher et al). This group had developed a more sophisticated approach using multiple roadway cues to detect the location of the vehicle in the lane under varying roadway conditions. Further validation work is needed to evaluate this methodology on all road conditions and against other drowsiness indicators to establish its validity.

Overall, the measures of driver performance show considerable promise as driver fatigue detection devices. These methods are not attempting to detect driver fatigue per se, but the effects of changes in the driver's state that are significant for road safety. These methods will also be of benefit for measuring other factors likely to adversely affect the functional capacity of the driver such as alcohol or drugs.

It is notable that the aforementioned methodologies are currently being applied in commercially available vehicles. For example, one of the latest models produced by Citroen (Citroen C4) includes a lane tracking device as an optional feature. This device is designed to detect when the vehicle unexpectedly crosses lane markings or the road edge. The driver is warned of the occurrence through vibration of the seat on the side where the lane infringement has occurred. No information is available on the effectiveness of this technology under Australian road conditions or on driver acceptance.

3. Combined driver state and performance measures

The approaches most likely to be successful for on-road driver fatigue detection in the longer term will be those that combine driver state and driver performance measures (e.g., Heitmann, Guttkuhn, Aguirre, Trutschel & Moore, 2001; Ladstaetter & Mahler, 2001). An approach of this kind will provide the most direct evidence of driver alertness and its relationship with driving capacity. The European Union has adopted this approach in a recently completed AWAKE (System for Effective Assessment of Driver Vigilance and Warning According to Traffic Risk Estimation) project (e.g., Bouverie, 2004). The aim of this project was to demonstrate the technological feasibility of driver vigilance monitoring systems and to look at the non-technical issues that can influence the use of such systems. The project employed driver state measures including eyelid movement, changes in steering grip and driver behaviour including lane tracking, use of accelerator and brake and steering position. These measures were then combined and evaluated against an assessment of current traffic risk obtained from digital navigation maps, anti-collision devices, driver gaze sensors and odometer readings. The project has produced a series of design guidelines for the assessment of driver vigilance and warning signals. These guidelines are comprehensive and although there are still a large number of unanswered research questions, they are likely to have considerable impact on the implementation of fatigue detection devices in the future.

4. Generic driver assistance and warning devices
There is a large amount of research and development on driver assistance systems (e.g., Fletcher, Apostoloff, Petersson & Zelinsky, 2003; Onken & Feraric, 1997). All of these systems focus on providing information to drivers that will facilitate their driving and warn them of threats to driving safety. These systems will also, therefore, function as devices that should respond to the effects of drowsy driving in the same way as the measures of driver performance designed specifically for driver fatigue discussed above. In the main, the road safety problems for these systems are the same; relating mainly to when and how the information is conveyed to the driver. Work by a group of researchers at Carnegie Mellon University (Ayoub, Grace & Steinfeld, 2003) has looked at the attitudes of experts and users (i.e., drivers) towards fatigue detection devices and the type of information that would be most readily accepted by users. Interestingly, the findings suggest that warning devices should be able to be turned off or have their volume modified significantly, clearly reducing their effectiveness. Similarly, the AWAKE project concluded that drivers should be trained in appropriately responding to warning devices, especially if they occur infrequently as this may result in the problem of startle effects which can negatively affect driver safety.

Further research is needed on different approaches to providing warning to drivers of increased safety risk. Other approaches to driver assistance and warning signals which have been evaluated include vibration of the seat and force feedback through the steering wheel in response to lane deviations. A laboratory study by Heitmann, Guttkuhn, Aguirre, Trutshchel and Moore (2001), for example, found that seat vibration had benefits for both warning drivers and re-arousing drivers, especially when they were experiencing intermediate levels of sleepiness. This was a pilot study, however, and the method needs more validation under simulation and on-road conditions. The driver assistance system developed by the group at the Australian National University (Fletcher et al) includes a force feedback component administered through the steering wheel. The degree of vibrotactile stimulation given is proportional to the extent of lateral deviation of the vehicle which provides both a warning to the driver and encourages them to correct the lane deviation. This novel approach clearly has some potential problems of conflict with driver intention, and would need to be evaluated very carefully before it could be implemented as a component of a functional on-road fatigue monitoring device.

**Summary**

The aim of driver fatigue warning devices is to provide information to the driver that their alertness is below a level compatible with safe operation of a vehicle. There is evidence that such warnings are useful to drivers who may be aware that drowsiness is increasing, but not aware of the impact of the drowsiness on their driving capacity. These devices may have additional benefits for drivers. For example, if the warning occurs early enough in the development of fatigue, such devices could enhance driver alertness sufficient to avoid a collision, although many of the devices currently under development, especially the driver state measures, will be detecting later stage fatigue which is unlikely to be overcome by a short period of stimulation such as a warning signal.

Some of the problems with the fatigue detection devices currently under development include the stage of drowsiness that is being detected, the focus of the measure on driver state (associated with the abovementioned difficulties) or the effects on driver performance (which may not be sensitive to only driver fatigue), and the timing and nature of the warnings used. More research and development is needed before effective fatigue monitoring devices are standard features in on-road vehicles. Some significant advances have been made, however, especially the AWAKE project of the European Union.

**Table 1: Summary of fatigue monitoring devices**

| **Changes in eye movement** | | |
|---|---|---|
| **Approach/System** | **Reference** | **Technique** |
| Tracking of gaze | Liu, Fengliang & Fujimura (2002). | Eye detection and tracking method using infra-red light and appearance-based object recognition. Allows eye tracking in low light. |
| Tracking of gaze | Perez, Cordoba, Garcia, Mendez & Munoz (2003). | Eye camera follows head movements by keeping pupil cental, uses infrared light to produce corneal glints that are picked up by camera to detect pupil-glint vectors. |
| Tracking of gaze | Eriksson & Papanikotopoulos (1997);<br>Heitmann, Guttkuhn, Aguirre, Trutschel & Moore (2001);<br>Singh & Panikolopoulos (1999);<br>Veeraraghavan & Papanikolpoulos (2001);<br>Wahlstrom, Masoud & Papanikolpoulos (2003). | Tracks eye using human skin colour properties then used a range of methods for detecting the eye including most recently infrared light bursts to identify the pupil and track movement. |
| Tracking of gaze | Zhu & Qiang (2004). | Video cameras capture images of the driver's face and a number of cues including eye gaze direction are used to infer driver states such as fatigue. |
| Blink behaviour | Svennson (2004). | Validation of Electrooculogram for fatigue detection using EEG and self-reported drowsiness. Blink behaviour changes with increasing fatigue, but large individual differences. |
| Facial tracking | Gu, Hi & Zhu (2002). | Uses Infra-red light to locate pupils and detect head motion then Kalman filtering to predict facial feature locations so tracking more than simply changes in the eye, uses predictive analysis to cope with facial occlusion problems. |
| Eye closure (PERCLOS) | Federal Highway Administration, Office of Motor Carriers (1998);<br>Dinges, Mallis, Maislin & Powell (1998);<br>Grace, Byrne, Bierman, Legrand, Gricourt, Davis, Staszewski 7 Carnahan (1998). | PERCLOS is a video-based method of measuring slow eye closure using trained observers to make judgements of eye closure from moment to moment. Evaluated against performance measures of lapses in attention using the Psychomotor Vigilance test (PVT). Showed reasonable correlations between eye closure and lapses. |
| Eye closure | Parmar & Hiscocks (2002). | Automated detection of eye closure by using video imaging of the face then computation methods for locating the eyes and changes in intensity to determine whether eyes are open or closed. Responds as closed eye if eye is closed for five consecutive frames or more. |
| Eye Blink | Ito, Mita, Kozuka, Nakano &Yamamoto (2002). | Measures the blink rate of a driver in real time via motion picture processing from which driver states are inferred. |
| Eye closure, gaze and blink rates (faceLAB) | Longhurst (2002). | Automated detection of eye closure, gaze and blink rates. Uses twin video cameras and feature detection to estimate head pose and fast tracking recovery to cope with temporary loss of the face, low light. Copes with sunglasses by estimating the direction of face using the direction the nose is pointing. Validated in simulator studies, evaluated using the Perclos methodology, |

| Physiological measures | | |
|---|---|---|
| **Approach/System** | **Reference** | **Technique** |
| EEG measures | Lal, Craig, Boord, Kirkup & Nguyan (2003). | Validation of EEG measurement as a tool for assessing fatigue using a simulator task. Methodology needs to be evaluated on-road. |
| **Driver performance measures** | | |
| **Approach/System** | **Reference** | **Technique** |
| Lane tracking | Wijesoma, Kodogoda & Balasuriya (2004). | Uses two-dimensional ladar sensing and extended Kalman filtering for fast detection and tracking of road curbs |
| Lane tracking | Apostoloff & Zelinsky (2003);<br>Fletcher, Apostoloff, Chen & Zelinsky (2001). | Attempts to overcome problems of previous lane tracking methodologies that use single cues relating to the edges of the lane such as centre lines or edge markings but which cannot cope with changes in road characteristics and lighting changes. This approach uses the Distillation Algorithm to combine a number of available visual cues (captured by video camera) which together provide robust estimates of the location on the vehicle in the lane, even when some of the main features are missing. |
| Lane tracking | Bertozzi & Broggi (1996);<br>Bertozzi & Broggi (1998);<br>Broggi (1995);<br>Broggi (1998);<br>Broggi (2003). | A lane tracking device based on geometrical transform and morphological processing. Under low lighting conditions the system can detect roadway lines on flat and structured roads. |
| Lane tracking | Chang, Lin, Hsu & Wu (2003). | Detects lane departure with a vision-based system that monitors the sight in front of the car. |
| Lane tracking (YARF) | Kluge (1997). | Assess the robustness of two lane tracking methods employed by the YARF (Yet Another Road Follower) system for locating the white road strips. |
| Vehicle lateral position and steering wheel input | Pilutti & Ulsov (1995);<br>Pilutti & Ulsov (1998). | Uses lateral position and steering wheel input to detect driver fatigue. |

| Multiple measures for monitoring driver fatigue | | |
|---|---|---|
| **Approach/System** | **Reference** | **Technique** |
| Multiple measures of driver alertness | Heitmann, Guttkuhn, Aguirre, Trutschel & Moore (2001). | Used multiple measures of driver alertness, including head position sensor (MINDS system), Eye-gaze system, Pupillometry measures Safety Scope and Mayo Pupillometry system. Used an in-seat vibration system to attempt to increase driver alertness to current state. Tested in simulator and found that no single measure was sensitive or reliable for quantifying driver fatigue. Suggest using a neural-fuzzy hybrid system to integrate multiple measures of alertness change. In-seat vibration methodology was promising, but most effective at intermediate sleepiness levels |
| Predicting fatigue-related crashes using lane tracking, eye-closure and changes in physiological state | Ladstaetter & Mahler (2001);<br>Rimini, Manstetten, Altmueller, Ladstaetter & Mahler (2001). | Used a range of physiological measures including ECG, EEG, EOG Skin temperature and impedance, Pulse and oxygen saturation in blood, respiration frequency and head movements, eye closure and lane tracking to predict crashes in simulations involving high stress driving (fog) and long driving stints. Showed that lane tracking predicted crashes. Further analysis is needed to evaluate relationships between other variables |
| AWAKE project | Boverie (2004). | Uses multiple parameters to detect real time hypovigilance and drowsiness while driving. Parameters for driver hypovigilance include eyelid changes and steering grip change and for driver behaviour include lane tracking, use of accelerator and brake and steering position. This information is matched with data on traffic risk including information from digital navigation maps, a positioning system, anti-collision radar, odometer and driver gaze direction sensor. If all of this information signals risk, a driver warning system is activated. The nature and level of the warning can be modified including user control of acoustic, visual and colour, and haptic parameters. The system is currently being piloted. |

| Approach/System | Reference | Technique |
|---|---|---|
| **Generic driver evaluation and warning systems** | | |
| DriveCam program | www.DriveCam.com | This system attempts to use video technology to detect high risk driving habits and is being marketed to commercial fleets as a method of improving driver safety and reducing insurance premiums. The system uses video camera to record the information drivers see and hear 10 seconds before and after an unexpected event such as erratic driving or a crash. The camera is triggered by high G-force levels due for example, to hard braking or accelerating or poor cornering. This information can then be downloaded by managers and reviewed. |
| Vision-based vehicle behaviour monitoring and warning system | Chang, Lin, Hsu & Wu (2003). | System uses video camera to collect information on lane tracking and preceding car tracking. Decision algorithm or Fussy Neural network methodology is used to determine whether the vehicle behaviour is at risk or not. An unspecified warning would then be applied. |
| Driver Assisting System (DAISY) | Onken & Feraric (1997). | Used a neural networks approach to model a trained driver. Demonstrates the potential use of this approach in a driver assistance system, including warning drivers of higher risk situations. The method has not been applied to the road. |
| Driver Assistance system | Fletcher, Apostoloff, Petersson & Zelinsky (2003);<br>Fletcher, Petersson & Zelinsky (2003). | Uses faceLAB to monitor the driver, and the Distillation algorithm to monitor driver performance (lane tracking and obstacle detection and tracking). Feedback on deviations in lane tracking are provided to the driver using force feedback to the steering wheel which is proportional to the amount of lateral offset estimated by the lane tracker. Further validation is needed to test this methodology. |
| User-centred Drowsy Driver detection and warning system | Ayoob, Grace & Steinfeld (2003). | This project focussed on the development of an acceptable warning system that will alert drivers and encourage safe behaviour. Through a qualitative assessment of usability involving experts and drivers, a drowsiness warning was developed which can be modified in sensitivity, sound type and volume that can be disabled by drivers. This system will be evaluated by drivers. |

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