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A REVIEW OF IN-VEHICLE SLEEPINESS DETECTION DEVICES

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Executive summary

Terms of reference. This review of in-vehicle sleepiness detection devices is a deliverable under the Department for Transport (DfT) funded '*Evaluation of Sleepiness Detection Devices*' contract.

Review. Many sleepiness detection devices have been developed. However, some of these are unsuitable for detecting sleepiness in drivers, due to a variety of factors, such as insensitivity to the early stages sleepiness, intrusiveness and driver acceptance issues. The overall purpose of this review is to outline and analyse current developments in the field and to identify a subset of sleepiness detection devices that are sufficiently promising for use in driving to be considered for possible future evaluations.

The review has identified sleepiness detection devices and predictive models that are currently available, some of which are commercial devices and others that are prototypes. These devices have been allocated into five categories as follows:

- based on physiological measures correlated with sleepiness;
- using physical variables such as activity and movement;
- based on behavioural indices including performance or activity directly related to the driving task, for example, steering wheel patterns;
- using models of fatigue, including the use of prior sleep history;
- combining elements of the above methods.

The review has assessed the sensitivity of the devices (where the information is available), validation issues, intrusiveness and likely driver acceptance, as well as the current market status of the devices and known operational problems. Following categorisation of the devices according to their basis of operation (for example, physiological, steering wheel movements or model-based), it was concluded that those based on physiological measures such as the EEG and skin resistance are too intrusive, and that measures of physical activity such as wrist or head movement are not sufficiently sensitive.

Some devices based upon measures of eye activity were considered to be suitable, depending on the way in which measures were taken, and those considered as potential candidate devices for further evaluation have been identified. The use of model-based techniques to identify increased likelihood of sleepiness is a promising approach, particularly when used in combination with other real time measures such as eye activity and steering wheel movements.

A subset of devices has been identified as potentially being worth evaluating in an experimental study. These are as follows:

- CoPilot
- ETS-PC Eye Tracking System
- FaceLAB 2.0
- MTI AM eye
- Onguard
- OptalertTM
- PERCLOS
- Smart Eye
- APL Drowsy Driver System
- DAS 2000 Road Alert System (methodology)
- SAMG-3Steer
- Sleep Watch

- ASTiD
- SAFETRAC
- SmartCar Driver Behaviour

Within this study, it is important to clarify the purpose of sleepiness detection devices. Such a device is intended to warn drivers of unexpected sleepiness, and is in no way intended to ‘keep the driver awake’. In particular, within commercial driving settings, it is emphasised that driver scheduling seeks to ensure that the driver has sufficient opportunity within each day to obtain adequate sleep, and within driving periods has time available to take regular breaks. This approach is key to fatigue management for both commercial and non-commercial drivers, and the role of sleepiness detection devices should only be seen as a fall-back safety aid.

1 Introduction

Driver sleepiness and falling asleep at the wheel are considered to cause a significant proportion (potentially up to 30%) of road traffic accidents, particularly during night driving (Folkard, 1997) and where adequate sleep has not been obtained during the previous 24 or more hours (Kecklund and Åkerstedt, 1993; Horne and Reyner, 1995; Lenne et al, 1997; Lyznicki et al, 1998). The best approach to preventing sleepiness at the wheel is to ensure that the driver is sufficiently rested before the journey commences, and to take regular breaks from driving, usually recommended to be about every two hours (Horne and Reyner, 1996). Should the driver become aware of sleepiness while driving, then it is suggested that a break for a short recuperative nap is taken (Gillberg et al, 1996), or to consume some caffeine (such as, a cup of coffee) (Horne and Reyner, 1996), preferably in addition to a nap.

However, not withstanding this advice, there has been considerable interest in developing a sleepiness detection device that warns the driver that he is becoming sleepy, for example, by sounding a warning tone or providing a vocal instruction to 'take a break'. Only relatively recently have devices been developed that may be sufficiently sensitive to detect the signs of sleepiness sufficiently early while at the same time being non-intrusive and acceptable to the driver. The latter criteria are essential for a sleepiness detection device to be used routinely on a day-to-day basis.

The purpose of a sleepiness detection device is to warn of unexpected sleepiness, and is in no way intended to 'keep the driver awake'. In particular, within commercial driving settings, it is emphasised that driver scheduling seeks to ensure that the driver has sufficient opportunity within each day to obtain adequate sleep, and within driving periods has time available to take regular breaks. This approach is key to fatigue management for both commercial and non-commercial drivers. Nevertheless, despite attention to these factors, there remains a perceived need for a device that detects driver sleepiness, thus acting as a final fall-back safety aid.

The requirements for a sleepiness detection device are the ability to detect the onset of sleepiness at an early stage and an effective warning mechanism with a means of alerting the driver. The device should also be non-intrusive and acceptable to the driver. This means that it should not require the driver to wear unacceptable attachments, for example, such as electrodes or helmet-mounted devices that are used in laboratory and industrial environments. The way the information gained on sleepiness is used, for example, by recording the occurrence of alerts, needs to be acceptable.

This review analyses the current status of sleepiness detection devices that are commercially available or in the late stages of development. It focuses on those that are suitable for the driving task, although mentions some others intended specifically for other contexts. The devices have been categorised into five types, as follows:

- based on physiological measures correlated with sleepiness;
- using physical variables such as activity and movement;
- behavioural indices including performance or activity directly related to the driving task, for example, steering wheel patterns;
- model-based, including the use of prior sleep history;
- a combination of the above methods.

The review assesses the sensitivity of the devices (where the information is available), validation issues and likely driver acceptance, as well as the current market status of the device and known operational problems. The review will not cover fitness-for-duty tests (readiness-to-perform) as these are not generally considered to be sleepiness detection devices.

2 Methodology

2.1 Databases and keywords used in the search for devices and associated scientific and technical information

To identify potential devices and associated technical information, the keywords used for searching were: ‘alertness detector’; ‘alertness detection device’; ‘alertness device’; ‘alertness monitor’. This was repeated using ‘sleepiness’, ‘sleep’ and ‘drowsiness’ each to replace ‘alertness’. Other keywords were ‘eye blinking and sleepiness’.

The databases and internet search engines used for the information search were ‘PubMed’, ‘PsychInfo’, ‘Scopus’, ‘Google’, and ‘Google Scholar’. The following patent databases were also searched: ‘European patents database’, ‘US patents database’, and ‘Worldwide patents database’.

2.2 Categorisation of devices

A table for each of the device categories is included (see Appendices), identifying the individual devices available and their characteristics (listed are as follows):

- the name of the device;
- the basis of the physiological, physical, behavioural or model-based operation;
- operational, validation, assessment and market status, for example, whether in routine use, tested in laboratory, validated in operational setting, and whether available commercially;
- intrusiveness and likely operator acceptance issues;
- the limitations on use, for example, effectiveness under conditions of environmental noise or variable light levels, and also whether they are relevant only to a specified occupational setting;
- the strategy and format of warnings or alerts, for example, auditory tone, vocal instruction, visual display or other;
- contact details of supplier;
- key references (see ‘References’ section of this document);
- suitability of the device for inclusion in the subset of up to 15 devices for experimental evaluation, including reasons.

A separate table is provided in the Appendix for each of the five device categories.

2.3 Assessment of scientific and practical issues of the sleepiness detection devices

An analysis of the scientific evidence for the usefulness of the measures currently used in sleepiness detection devices is provided. Their relationships with sleepiness and performance are described, and general problems and pitfalls associated with their practical use in road transportation are identified.

3 Results

3.1 Physiological sleepiness detection devices

Full details of the devices are shown in the Appendix, and include those based on features of eye activity, the electroencephalogram (EEG, representing brain electrical activity) and electrodermal activity (galvanic skin resistance). A summary table is given below.

Name of device	***Physiological, physical, behavioural or model-based operation***	***Potentially to further evaluate***	***Reasons for inclusion/exclusion***
Eye-based			
AlertDriver	Monitors eye droop, pupil occlusion and eye closure via a camera. Uses image neural nets, fuzzy logic to locate subject's eyes. Is also model-based.	Exclude	Does not work when the driver is wearing sunglasses.
CoPilot	See also PERCLOS system upon which CoPilot is based. Detects percentage of time eyes are closed over a specified time interval (PERCLOS system) via infrared camera system	Include	Potential candidate provided that the device is effective in both daylight and night-time conditions.
DaimlerChrysler Eye-Gaze Detection System	Measures eye gaze via dashboard camera.	Include (provided it can be retrofitted to all cars)	Potential candidate.
Expresseye	Measures fixation, gaze control and saccadic eye movements to a target. Uses infrared light corneal reflection technique	Exclude	Unsuitable due to head-mounted optics, so is highly intrusive.
EyeHead	Measures eye position, head position and eye to point of fixation distance. Uses a magnetic head tracker	Exclude	Unsuitable due to head-mounted optics, so is highly intrusive.
Eye-Gaze System	Measures gaze-direction via corneal reflection technique. Also measures pupil diameter, blinking, and eye fixation.	Exclude	Unsuitable due to requiring a head set to be worn, so is highly intrusive.
Eyeputer	Records eye movements via corneal reflection technique	Exclude	Unsuitable due to need for headset, so is highly intrusive.
ETS-PC Eye Tracking System	Detects eye closure via a camera	Include	Potential candidate.
FaceLAB 2.0	Measures eye-gaze and eye closure. Uses PERCLOS fatigue assessment scale	Include	Potential candidate.
IM-Blinkometer	Detects blinks using a piezoelectric adhesive disk attached to canthus of the eye	Exclude	Not suitable due to sensor attached to face/eye, so is highly intrusive.
MTI AM eye	Detects eye blinks. Measures ratio of closed to open eyes to detect sleepiness. Uses infrared reflectance	Include	Potential candidate.
Nissan Drowsy/ Inattentive Driver Warning	Uses image processing to monitor eyelid movements	Exclude	Insufficient information to evaluate.
Onguard	Measures eye closure, activates an	Include	Potential candidate.

Name of device	*Physiological, physical, behavioural or model-based operation*	*Potentially to further evaluate*	*Reasons for inclusion/exclusion*
	alarm after 0.5s closure period. Uses infrared reflectance.		
Optalert™	Uses infrared oculography to detect eyelid movements during blinking and eye closure. The system is being further developed to measure inter-saccade interval (may be more prediction of alertness, and also detect absence of changes in gaze).	Include	Likely candidate. Although the system requires glasses to be worn, these are lightweight and can accept a variety of lens types. Therefore, although the system is potentially intrusive, this may be less than most other similar systems. The independent validation in a range of occupational setting (eg Maritime) supports this.
PERCLOS	Detects eye closure using infrared, retinal-reflectance device. Measures duration of blinks and eye closures, and proportion of time eyes closed over a specified time interval.	Include	Potential candidate if problems with night driving resolved.
Photo Driven Alert System	Worn on ear and measures blink rate	Exclude	Unsuitable due to need to wear device on the ear and is incompatible with wearing glasses.
SafetyScopeTM	Ocular system in quantifying sleepiness.	Exclude	Unsuitable due to head-mounted optics, hence intrusive.
Smart Eye	Detects head position and point of gaze via image processing	Include	Potential candidate
Toyota Driver Drowsiness Detection and Warning System	Detects eyelid movement using camera mounted on rear-view mirror	Exclude	Not possible to retrofit due to implementation of warnings
Vehicle Drivers Anti-Dozing Aid (VDAD)	Measures eye closure and head movement via infrared reflectance. Developed by US military.	Exclude	Unsuitable due to need to wear device on ear, hence intrusive
EEG-based			
ABM Drowsiness Monitoring Device (DMD)	Records EEG via telemetry to detect drowsiness	Exclude	Unlikely to be acceptable for routine use without the introduction of a 'dry' electrode system.
EEG Based Algorithm to Detect Different Levels of Driver Fatigue	Uses delta, theta, alpha and beta activity of the EEG to detect 'early, medium and late' sleepiness	Exclude	Unlikely to be acceptable for routine use without the introduction of a 'dry' electrode system.
GSR-based			
Engine Driver Vigilance Telemetric Control System 3rd generation (EDVTCS)	Measures electrodermal activity and electrodermal reactions. No information on specific parameters	Exclude	Unlikely to work under a range of different conditions.

Table 1. Summary details of sleepiness detection devices based on physiological measures

3.1.1 Sleepiness detection devices based on eye activity

Many sleepiness detection devices are based upon indices of eye activity that are correlated with sleepiness. These include blinking behaviour, saccadic eye movement patterns (that is, changes in fixation point), pupil size, eye point of regard and eye closure for brief periods. There is a strong relationship between sleepiness and eye activity, although the indices are also affected by other factors such as visual task information processing demands and environmental conditions such as ambient illumination.

Several systems measure eye closure and closely related phenomena, such as eye droop and slow eye movements. Eye closure was investigated by Wierwille et al (1994) and Hyoki et al (1998). The development of slow eye movements as sleepiness increased was described by Torsvall and Åkerstedt (1987, 1989) during train driving operations; Hyoki et al (1998) also measured changes in the velocity of eye movements related to sleepiness. An example of a system that detects eye closure and eye droop is the PERCLOS system, developed by Dinges and Grace (1998) and Wierwille (1999), and implemented commercially as CoPilot. In these devices, image processing procedures are used to determine the proportion of time that eye closure has occurred over a specified interval. Methods based upon eye closure will detect sleepiness in a time frame of around a second.

As an alternative, potentially more sensitive measure than eye closure, several systems are based upon the measurement of blinks. Various blink characteristics such as rate, duration and amplitude, have been investigated extensively in relation to sleepiness and fatigue. Increased blink duration and rate and reduced amplitude were reported by Stern et al (1984, 1994) with increasing time on task. Similarly, Morris and Miller (1996) found that blink amplitude, blink rate and long eye closures were good predictors of error rate during a 4.5-hr simulated flight. With regard to sleepiness, Caffier et al (2003) reported that blink duration, reopening time and the proportion of blinks with a long closure duration increased reliably with increasing sleepiness. Johns et al (2005) have developed a sleepiness detection device, Optalert, based upon the amplitude and velocity of eyelid closure and re-opening during blinks to identify the onset of sleepiness.

However, while blinks are clearly sensitive to sleepiness, there is a complex relationship between blinking activity, visual information processing (which usually suppresses blinks) and sleepiness. For example, blink frequency and duration were decreased by increasing task demands during a flying task (Wilson et al, 1994; Brookings et al, 1996). Similarly, hazardous roadway curves produced lowered blink rates in drivers (Richter et al, 1998), and Summala et al (1999) found that while blink frequency was increased during overnight driving, an increase in the visual task demands, such as meeting oncoming traffic, resulted in a decrease in blink frequency. Therefore sleepiness detection devices based upon the analysis of blinks should be evaluated with due consideration to the visual demands of the driving task.

Pupil diameter has also been used as the basis for sleepiness devices. Sleepiness is associated with a decrease in pupil size (Lowenstein and Lowenfeld, 1962; Yoss et al, 1970; McLaren et al, 1992), although it is increased by high levels of cognitive demand (Beatty and Wagner, 1978; Backs and Walrath, 1992) as well as being affected by changes in illumination. Image processing techniques are used to measure pupil diameter automatically, and an example of this is the AlertDriver system (RSSB, 2002).

The main technologies that have been used to measure eye activity for the purposes of sleepiness detection are infrared reflectance devices and the analysis of video imagery. The infrared technique typically uses a transmitter and receiver that are mounted on a pair of spectacles worn by the driver, and directs a beam of infrared light at the eyelids of the driver (Webster and Leder, 1997; Johns et al, 2005). The method may allow the driver to wear prescription glasses or sunglasses if they are suitably modified. Image analysis of eye activity is achieved using a dashboard-mounted camera pointed at the driver's face, and uses image processing techniques to locate the driver's head and eye positions, although operational problems may be encountered with large head movements. They do however enable eye point of regard to be measured through the combined use of head and eye position; eye point of regard can provide an indication of the driver's focus of visual attention, and therefore may provide information additional to the prediction of sleepiness. Both technologies can have difficulty coping with the wide range of illumination levels typically encountered while driving, such as bright sunlight, darkness and rainy conditions. Therefore a careful assessment of the practical issues associated with measuring eye activity to detect sleepiness is required.

3.1.2 EEG-based sleepiness detection devices

The EEG is a sensitive measure of sleepiness (Belyavin and Wright, 1987; Ogilvie et al, 1991; Makeig and Inlow, 1993; Lafrance et al, 2000) where changes in theta (3.5-7.5Hz), alpha (8-13Hz) and beta (14-30Hz) frequencies are associated with brief periods of sleepiness (microsleeps) and the onset of sleep. Instabilities in the EEG, involving short-duration changes in alpha and theta activity, are associated with falling asleep while carrying out a monotonous task (Wright et al, 1987). As with eye activity, the EEG is affected by factors such as workload (Wilson et al, 1994). However, the changes in the EEG as sleepiness develops are sufficiently distinct that sleepiness can be reliably identified, although the simultaneous use of the EOG is highly recommended.

Several algorithms have been developed that predict sleepiness using the EEG. Makeig et al (1995) has used multiple regression of EEG variables recorded from several locations on the head, along with the EOG to identify sleepiness. The method learns an individual's specific EEG pattern and computes a continuously updated sleepiness score. A further algorithm, the so-called CRI-EEG developed by Consolidated Research Inc, uses the occipital EEG analysed over a 2s time period, although no information is given on which measures of the EEG were used to detect sleepiness. A neural network method using wavelet analysis (Wilson and Bracewell, 2000) has also been used to identify sleepiness, and the authors indicate that it can classify the EEG as representing either alertness or sleepiness.

However, the above methods have not as yet been implemented as a sleepiness detection device as no hardware is included to record and analyse the EEG data, and a physical alerting system is not yet incorporated, although in some cases the warning scheme or parameter is in place (for example, Makeig et al, 1995). Furthermore, the practical problems associated with using the EEG as a sleepiness detector, such as the requirement for scalp electrodes, have not been addressed. Relatively non-intrusive methods of recording the EEG have been developed over the past few years, and used in an alertness device developed by Advanced Brain Monitoring, Inc. (2002). In this system, the EEG electrodes are housed in a baseball cap with amplification being carried out by a microprocessor situated at the back of the cap. The signals may be transmitted to a base station using telemetry. However, the entire system has not yet been systematically validated in terms of accuracy to detect sleepiness.

A further EEG-based sleepiness detection system that will include a hardware implementation has been developed by Lal et al (2003). The method uses delta, theta, alpha and beta activity, and is described as detecting 'early, medium and late' levels of sleepiness. There is however no evidence published regarding the predictive capability of the algorithm. The authors are currently developing a hardware implementation of the methodology using wireless technology (personal communication) to enable EEGs to be recorded in occupational settings. Problems associated with physiological and environmental artefacts have not been addressed.

Although the systems described above appear to be promising, the conclusion at present is that the technology for recording EEGs is not yet sufficiently mature for use by drivers on a day-to day, routine basis. Also, the driver is required to wear a cap or headband, which may be possibly intrusive.

3.1.3 Devices based on electrodermal activity (galvanic skin resistance)

Skin resistance increases with sleepiness and fatigue (Nishimura and Nagumo, 1985; Boucsein and Ottmann, 1996), although the changes have been found to be unrelated to specific incidences of sleepiness or sleep (Wright et al, 2001). Furthermore, electrodermal activity is affected by many factors, including biophysical properties of the skin (Adhoute al al, 1992), psychological stress

(Trimmel et al, 2003), workload (Collet et al, 2003), individual differences (Wilken et al, 1999) and variations in environmental factors such as noise, physical movement and humidity.

A sleepiness detection device, the Engine Driver Vigilance Telemetric Control System (EDVTCS; Neurocom, 2006), based on electrodermal activity, is currently in use within the Russian railway system. However, no independent validation information has been found, although the device has been operational for several years. It is based on scientific evidence that skin resistance increases with sleepiness. The device has the advantage of being relatively unobtrusive, as it is worn in the form of a wrist-watch; however, the above factors which modify skin resistance in addition to sleepiness are likely to reduce the effectiveness of the device.

A further device, the 'Sensewear Pro' (Armband, 2006) also uses skin resistance along with other measures, including wrist movement (actigraphy), and claims to detect sleep with a 95% accuracy. While the use of a combination of measures may offer advantages over single parameters, the device is unlikely to be suitable for alerting drivers, since it would appear to detect sleep rather than sleepiness and is therefore insufficiently sensitive.

3.2 Sleepiness detection devices based on physical activity, including wrist activity and head movements

Full details of the devices are shown in Table A2 of the Appendix. A summary table is given below.

Name of device	***Physiological, physical, behavioural or model-based operation***	***Potentially to further evaluate***	***Reasons for inclusion/exclusion***
Actiwatch-alert	Measures wrist inactivity associated with sleep	Exclude	Unsuitable because time basis of alert is too long for driving context (5 mins of sleepiness required before alert). Developed for use in aviation environment.
Doze Alert	Measures head-tilt as sleep occurs	Exclude	Insufficiently sensitive as only detects when asleep.
Driver Alert Warning Device	Measures head-tilt via pressure device on neck	Exclude	Insufficiently sensitive as only detects when asleep.
EPAM	Measures wrist inactivity associated with sleep	Exclude	Insufficiently sensitive as only detects when asleep.
MINDStim (MicroNod Detection System)	Monitors head movements. Learns typical patterns of movement, and detects those associated with drowsiness	Exclude	Head movements unlikely to be an effective indicator of early stages of drowsiness. Also device has potential safety implications
Proximity Array Sensing System (PASS)	Detects brief head movements associated with sleepiness. Uses system of electromagnetic fields to detect micro sleeps	Exclude	Insufficiently sensitive as only detects when asleep.
StayAlert	Detects head droop by detecting chin contact with device worn round the neck	Exclude	Insufficiently sensitive as only detects when asleep.

Table 2. Summary details of sleepiness detection devices based on measures of physical activity

The measurement of actigraphy has frequently been used in research on sleep and circadian rhythms and to investigate patterns of rest and activity (Sadeh et al, 1995). The technique is based upon the difference in the amount of body movement present during sleep compared with wakefulness (Pollack et al, 2001). These authors, along with Lockley et al (1999), verified that consolidated sleep could be differentiated from wakefulness, but that short transitions between sleep and wakefulness are not accurately identified (Chambers, 1992). This means that short periods of waking may not be identified. The converse has also been found, that is, brief periods of sleep or sleepiness occurring when an individual is required to be awake are also not reliably identified by measuring wrist inactivity. This measure has been used as the basis of a sleepiness detection device, the 'Actiwatch Alert', developed for the UK Civil Aviation (Wright and McGown, 2004; Wright et al, 2005) for use by aircrew to minimise unplanned sleep during cruise. The method is however unsuitable for use by drivers because it requires a relatively long period of sleepiness or sleep (four to five minutes).

Wrist activity has been used to develop other sleepiness detectors, for example, EPAM (Redmond and Hegge, 1985) and Sensewear Pro (Armband, 2006); however, as with the 'Actiwatch Alert', a period of sleep of the order of several minutes is required to identify sleep. Several devices have been based upon the measurement of head movement, for example, 'MicroNod' (RSSB, 2002), and 'Driver Alert Warning Device' (Anderson et al, 2002), although as with wrist activity, a relatively long interval of sleepiness or sleep is required before an alert is activated. The use of head movements to detect sleepiness was investigated by Wright et al (2001) and was found to be similar to wrist activity with regard to sensitivity to the detection of sleep. Devices that are based upon the pattern of head movements of individual drivers, for example, by measuring head position and lateral movements while scanning the road, may however be more sensitive, although insufficient validation information is available. One such example is the 'Proximity Array Sensing System ' (PASS, 2006). In addition, many 'low tech' devices are available that sense, for example, head droop, and although some are available commercially, they are unsuitable due to lack of sensitivity.

3.3 Devices based on behavioural measures, including driver or operator performance or task-related activity, and secondary task performance

Full details of the devices are shown in Table A3 of the Appendix. A summary table is given below.

Name of device	*Physiological, physical, behavioural or model-based operation*	*Potentially to further evaluate*	*Reasons for inclusion/exclusion*
APRB/ACARP Device for Monitoring Haul Truck Operator Alertness	Uses secondary task to estimate alertness via an auditory and visual reaction time task (tailored to individuals). Used in mining industry trucks.	Exclude	Unsuitable as is secondary task.
DAS 2000 Road Alert System	Measures drivers' acceleration, braking, gear-changing, lane deviation and distances between vehicles.	Include	Potential candidate.
FMD – Fatigue Monitoring Device	Auditory and visual reaction time test. Response pads on steering wheel. Used in mining trucks.	Exclude	Unsuitable as is secondary task.
Roadguard	Is a secondary task comprising a reaction task. Only operates when vehicle is in top-gear.	Exclude	Unsuitable as is secondary task.
Safety Driver Advisor	Learns normal driver steering movements and detects deviations from normal. Comprises a driving time measure, a dashboard display of recommended rest-break times and a monitor of erratic steering behaviour. Recommended driving time is 2h for day, 1h for night	Exclude	Likely to be unsuitable due to the design of the warning system.
SAMG-3Steer	Monitors normal corrective movements of steering wheel	Include	Potential candidate.
Stay-A-Wake	Monitors speed and steering behaviour.	Exclude	Unsuitable due to design of warning system.
SAFETRAC	Uses measurement of lane deviations and steering movements	Include	Potential candidate.

Table 3. Summary details of sleepiness detection devices based on behavioural measures

Some sleepiness detection devices using behavioural measures are in routine use at present, including devices based upon responses to either the occupational task or a secondary, embedded task.

Devices identified for monitoring sleepiness-related behaviour in drivers were mainly based upon patterns of steering wheel movement, for example, Safety Driver Advisor (Haworth et al, 1989), Stay-A-Wake (Haworth et al, 1989) and Travalert (Travalert, 2006). The DAS2000 Road Alert System (DAS2000, 2006) monitors lane deviations, inter-vehicle distance, centre-line and hard-shoulder crossings. While these measures are non-intrusive, have a degree of face validity, can often be easily integrated with other in-vehicle technologies and warning systems could readily be implemented, they may be relatively insensitive to sleepiness per se, and are likely to be less effective than devices based upon eye activity. Used in combination with other methodology, however, they may operate acceptably, so should be considered for further evaluation. Based upon the devices identified, some of the warning systems are likely to be unacceptable because they could cause driver frustration or startle. For example, the 'Stay-A-Wake' system is likely to result in an unsafe startle reaction because a delayed response to a sleepiness warning causes the cruise control mechanism to be disabled and the vehicle's horn activated.

A range of devices employing secondary tasks are currently used in driving occupations in the mining industry. These operate by measuring response times to visual and auditory stimuli. Examples are the ARRB/ACARP (ACARP, 2006), used in coal mining trucks, and the FMD (Fatigue Monitoring Device; Hartley et al, 2000). A prototype secondary task-based system, 'Roadguard' (Haworth et al, 1989) also uses response time and is intended for more general driving contexts. However, sleepiness detection devices employing secondary tasks are usually considered intrusive to the main task, increasing workload and potentially impairing safety (for example, Verwey and Zaidel, 1999), and so have been rejected as unsuitable.

3.4 Model-based predictions of sleepiness

Full details of the devices are shown in Table A4 of the Appendix. A summary table is given below.

Name of device	*Physiological, physical, behavioural or model-based operation*	*Potentially to further evaluate*	*Reasons for inclusion/exclusion*
Fatigue Audit Interdyne System (FAID)	Mathematical model based on work/rest patterns.	Include (as part of a combined system)	Potential candidate, if part of a combined system e.g. based on a real-time measure.
Sleep Watch	Determines amount of sleep taken using wrist-worn accelerometer, and predicts and displays level of alertness on watch	Include	Potential candidate.
US Army Sleep Management System	Mathematical model based on work/rest patterns over last month and circadian influences to predict impaired performance	Include (as part of a combined system)	Potential candidate, probably as part of a combined system e.g. based on a real-time measure. Based on same system as Sleep Watch.

Table 4. Summary details of sleepiness detection devices that use model-based predictions of sleepiness

Mathematical models have been developed that predict sleepiness and alertness based upon a range of factors including circadian influences, time since sleep and duration of current work schedules (Spencer and Grundel, 1998). Such models have been validated in terms of their correlation with behaviour and validated subjective scales, such as the Karolinska Sleepiness Scale and Samn-Perelli Scale. The main application of the models to date has been in the assessment of duty schedules and rosters to predict likely levels of fatigue. Although they are not sleepiness detection devices as such, they may be used to predict the likely risk of sleepiness occurring. In particular they may be used in combination with real time measures such as eye activity or steering wheel patterns to identify sleepiness. For this reason, a description of several models available has been described below.

The 'Three-process Model of Alertness' developed by Folkard and Åkerstedt (1987) uses the amount of prior wakefulness and sleep as well as circadian influences to predict alertness and performance. The current predicted level of alertness is estimated on a scale of 1 to 16. The model identifies the level at which impaired performance and reduced alertness is likely to occur, as well as predicting the sleep latency and time of awakening during sleep periods. Various aspects of performance are considered, including reaction time, vigilance performance and risk of driving off the road. The current application of the model is to evaluate fatigue levels and sleep risk during work and rest schedules, and has been validated in applied settings, including driving and aviation.

Fletcher and Dawson (1998) developed the Fatigue Audit Interdyne System (FAID), which is a model based on sleep history and patterns of work and rest. Predicted fatigue scores may be output before a journey commences to assess the likelihood of excessive levels of fatigue. The FAID system has been validated in truck driving and aviation contexts. A further system for evaluating fatigue risk is based on an algorithm using fuzzy logic, in which the safety of a driver is identified using his/her estimated level of skill and current fatigue score (Jian and Yuanpeng, 2000). The model uses individual-specific measures to derive a skill-based variable and subsequently uses neural networks to compute an 'active safety factor'.

The above models enable sleepiness and fatigue to be predicted. The US Army has produced a model-based system for real-time use in military operations. The model uses sleep history and other factors including work/rest patterns and circadian influences to provide a Sleep Management System (SMS, 2006), which has now been developed commercially as a wrist-worn device known as the 'Sleep Watch' (SW, 2006). The device provides a continuous output of predicted alertness level (cited by Bekiaris and Nikolaou, 2002) along with warning alerts when critical levels are exceeded.

3.5 Devices based upon a combination of more than one approach or measure

Full details of the devices are shown in Table A5 of the Appendix. A summary table is given below.

Name of device	*Physiological, physical, behavioural or model-based operation*	*Potentially to further evaluate*	*Reasons for inclusion/exclusion*
Advisory System for Tired Drivers (ASTiD)	Uses model based on time of day, the quality of the driver's sleep in the last 24h, total driving time and monotonous conditions. Is combined with patterns of steering wheel movements, computes fatigue on a display panel.	Include	Potential candidate.
APL Drowsy Driver Detection System (DDS)	Uses doppler radar to measure speed, frequency, duration of eyelid closure, heart rate and respiration. Sleepiness based on general activity and eye activity monitoring.	Include	Potential candidate.
COMPTRACK	Uses EEG frequency analysis and secondary (tracking) task.	Exclude	Unsuitable because involves a secondary task.
Sensewear Pro	Combination of measures of Activity via accelerometers, skin temperature and near-body temperature. Detects sleep with 95% accuracy.	Exclude	Unsuitable due to being insufficiently sensitive to sleepiness.
SmartCar Driver Behaviour	Uses cameras to capture traffic information outside, and inside to detect head position. Synchronized with data acquisition from braking, gear changes and steering. Gaze direction measured by camera mounted on	Include	Potential candidate for methodology, i.e. combines eye movements, head position, and contextual driving

Name of device	*Physiological, physical, behavioural or model-based operation*	*Potentially to further evaluate*	*Reasons for inclusion/exclusion*
	a pair of glasses.		information.
Wearable Alertness Monitoring Guard	Detects eyelid closure via image analysis, reaction time, and head movement heart-rate	Exclude	Is unsuitable due to being helmet mounted.
SAFETRAC	Uses measurement of lane deviations and steering movements.	Include	Potential candidate.

Table 5. Summary details of sleepiness detection devices based on combination measures

Several devices use a combination of driver steering-wheel measures and other sleepiness detection approaches. 'ASTiD' (Cacciabue, 2004) combines information from the steering wheel and a mathematical model to predict sleepiness, and displays a computed 'fatigue index'. The system provides warnings and vocal instructions, and is currently being evaluated in field studies. Others, for example, SAFETRAC (2006) and an ASL system (RSSB, 2002), use eye activity measures combined with operator input patterns.

A combination of EEG measures and operator performance of a secondary tracking task is used by the COMPTRACK system (Makeig and Jolley, 1996) and two systems use multiple physiological and physical indices. These are the APL device, where eye movements, respiration and heart rate are used to indicate 'general' activity and eye activity, JHUAPL (1999); and Sensewear Pro (Armband, 2006), where activity is measured via accelerometers, and body heat flux and galvanic skin resistance recorded via electrodes on the skin. The latter device is able to detect incidences of sleep with an accuracy of 95% while APL may be more sensitive to sleepiness as it includes eye activity measures.

The physiologically-based systems are likely to be too intrusive with the exception of the APL device which uses Doppler radar to monitor the driver non-intrusively. The use of a secondary task in the driving environment is considered unacceptable for safety reasons. The combinations of steering wheel measures and eye activity parameters or predictive models would however appear to be a promising approach.

4 Discussion

This review demonstrated that sleepiness detection devices can be based upon a wide range of different parameters and that there is no single commonly accepted metric to detect driver fatigue in an operational context. Devices currently available can be classified into those based on physiological measures, including eye movements and the EEG; physical indices indicating movement such as wrist activity; behavioural measures including response time and steering wheel movement patterns; mathematical models predicting sleepiness from prior sleep history; and various combinations of each of these approaches. Within each of these categories, some devices were clearly inappropriate for detecting sleepiness during driving, while others appeared to be potentially useful and worth further consideration.

There have been a number of reviews of sleepiness detection devices. For example, Dinges and Mallis (1998) reviewed approaches to sleepiness detection in drivers, as well as issues and requirements for a reliable acceptable sleepiness detection device. Hartley et al (2000) identified the importance of validating these devices appropriately, as well as the way in which information from sleepiness devices should be used. Williamson and Chamberlain (2005) reviewed a range of sleepiness detection technologies and discussed their likely effectiveness and problems, such as the sleepiness level detected by the devices and the timing and nature of warning alerts to the driver. Overall, based upon information included in these sources, the requirements for a sleepiness detection device suitable for use while driving may be stated as follows:

- the ability to detect sleepiness at a sufficiently early stage, that is, before the likelihood of an accident is increased by sleepiness;

- absence, or a minimal rate of false alarms, that is, alerting the driver when sleepiness is not present;
- non-intrusiveness to the driver: that is, the device does not intrude on the ability of the driver to perform the driving task, or cause irritation, for example, by requiring the wearing of various attachments;
- a high level of driver-acceptance, whereby the device is seen to be acceptable, for example, in terms of how the data from the device is to be used, and that the driver perceives the device to be beneficial;
- understanding of whether and under what circumstances the use of sleepiness detection devices could be deemed mandatory;
- presence of an effective strategy and implementation of warning alerts to inform the driver of impending sleepiness and that he/she is unsafe to drive;
- the device operates effectively for all individuals, without the need for frequent individual calibration i.e. at the start of every journey;
- the device must operate under all environmental conditions, including bright sunlight, darkness and rain;
- there is a clear statement of the exact purpose of the device. For example, it should not be used to prolong the amount of time for which an individual can drive.

Within a driving context, the occurrence of sleepiness needs to be identified at an early stage. For example, a two-second period of eye closure could result in an accident. Devices need to be evaluated experimentally using sensitive analyses of the EEG and eye movements such that sleepiness preceding eye closure is detected. A significant proportion of the devices included in this review are based upon indices of eye activity, and while these may be among the most sensitive, they may also require a period of time to establish stable, statistically reliable thresholds in order to avoid causing false alarms. It is possible that devices based upon combinations of measures, such as predictive models and eye movements prove to be the most effective.

Concerning the false alarm rate, it may be argued that a zero false alarm rate is not achievable at all times. Detecting sleepiness with sufficient sensitivity for safety to be significantly enhanced may mean that there is a trade-off, with some false alarms occurring albeit sufficiently infrequently so as to be acceptable to the driver. However, the device must be better than driver self report at detecting fatigue, otherwise the acceptability and efficacy of the device is likely to be low.

The extent of intrusiveness caused by the detection device apparatus means that many devices based on sensitive measures of sleepiness, such as the EEG, are unsuitable for use by drivers. The technology available for recording EEGs is advancing so that, for example, in a military context where helmets are routinely worn, such recordings may conceivably be acceptable, via new developments in electro-optic or dry electrodes (Caldwell et al, 2004). However, any head-worn devices, even potentially the requirement for eye-glasses when these are otherwise unnecessary, are likely to be considered intrusive by drivers. An exception to this would be in certain safety-critical commercial operations (e.g. a truck driver carrying hazardous chemicals), where some degree of intrusiveness may have to be tolerated.

With regard to the strategy and implementation of warnings alerts to the driver, the most frequently used form is an auditory tone along with vocal instructions and visual displays. There is evidence that alerts provided to individuals who have become sleepy are only effective for a relatively short period of time, and therefore repeated alerts with differing intensity and action required may be more effective than a single stimulus. The design of appropriate warning systems is crucial to the development of an effective sleepiness detection system, and will, for the selected devices, be considered in the later phases of the project.

Individual differences affect the majority of measures upon which sleepiness detection systems are based. Physiological variables in general show variations between individuals, and eye behaviour is frequently associated with marked individual differences. As a particular example, the detection and measurement of eye activity parameters can be affected by the shape of the eye and by the colour of the iris, and so eye-based sleepiness detection devices need to be evaluated with regard to this. A further example is the use of predictive mathematical models; where the predictive sleepiness or fatigue scores are based upon group average responses, then a sleepiness detection system should be able to make an allowance for individual differences, for example, by inputting personal data. As with physiological measures and model-based sleepiness estimation, driver behaviour exhibits marked individual differences, and so systems based on vehicle-based parameters require assessment and analysis to ascertain their applicability to the driver population.

Integrating fatigue technology into the transport system

If put to the wrong use a technology could be dangerous to transportation safety; put to the correct use a technology could have the potential to benefit safety. Horberry et al (2001) argue that such devices will have to be considerably more accurate than drivers' own self reports if they are going to be used successfully by drivers to improve safety. If drivers do learn to rely on the technology because they believe it is accurate, then a technological failure could be catastrophic for the driver, with huge implications for product liability for the manufacturer. If the driver believes that the fatigue technology is misleading them it will be ignored totally, even if it accurately detects unsafe fatigue on some occasions: a situation that might also result in a catastrophe.

Conversely, commercial companies that have invested in fatigue technologies in their vehicles will be greatly tempted to rely on the assessment of their drivers by their technology, and trust less the drivers' feedback on their own state of fatigue. An in-vehicle technology that missed instances of driver fatigue could lead to companies setting unrealistic schedules that increased driver fatigue with consequent risk to public safety. A technology that was over-zealous in detecting fatigue might have implications for productivity.

Acceptability of the technologies for commercial vehicle operations

In terms of driver acceptance, a key issue is the legal position surrounding the way in which information obtained from sleepiness detection devices is used. This refers mainly although not exclusively to commercial driving operations, and is related to any mandatory requirement to use sleepiness detection devices.

The technologies will have considerable appeal to transport companies, but have less appeal to drivers (Horberry et al, 2001). This is because the technology invades drivers' privacy to a degree and introduces an element of supervision in an industry that has traditionally attracted people who like to work without close supervision. In-vehicle technologies will, however, have appeal to companies because they have the potential to shift the burden of managing fatigue away from company management and place it on to drivers[1]. If a validated technology is installed in the cab then the company management might believe it has met its obligations and is potentially absolved from further responsibility for providing safe and responsible trip schedules. Drivers can be left to their own devices to drive until the technology tells them not to. If the technology fails to detect fatigue and there is a crash then one resulting legal question is whether the fatigue detector manufacturer is liable for providing a defective product. But of course if the in-vehicle technology does cut crash rates then this will be an added attraction to install the technology, since there will be fewer legal cases and less down time for the vehicle fleet.

A consideration of the points discussed above has led to a preliminary indication of which devices may be suitable for experimental evaluation. A preliminary sift of the devices and methodologies likely to be worth further evaluation has resulted in the following:

- several of the eye activity based systems may be suitable (as indicated in Table 1);

[1] It should be noted that this argument is in direct contrast to current best practice regarding fatigue management in commercial driving operations, which stress the importance of shared responsibility.

- those based upon the EEG and galvanic skin resistance are considered too intrusive;
- devices based on wrist activity and head movements, are insufficiently sensitive for driving;
- of the mathematical models available, the Sleep Watch is likely to be worth evaluating because it is being produced as a physical entity that can be worn;
- among the devices based upon a combined approach, those using both steering wheel movement and a mathematical model predicting sleepiness (‘ASTiD’), and head position and traffic information (‘SmartCar’) appear suitable for testing.

5 Conclusion

This review has provided an initial evaluation of sleepiness detection devices. Although many devices for detecting sleepiness are available, most proved unsuitable for detecting sleepiness in drivers, due to a variety of factors, such as insensitivity to the early stages of sleepiness, intrusiveness and assumed driver acceptance issues.

The following conclusions may be drawn from the review:

- no single method exists that is commonly accepted to detect driver fatigue in an operational context;
- the review has identified sleepiness detection devices that are available commercially or as prototypes for use in drivers, and has analysed the scientific evidence for their effectiveness to warn drivers of sleepiness;
- following categorisation of the devices according to their basis of operation (for example, physiological, steering wheel movements or model-based), it was concluded that those based on physiological measures such as the EEG and skin resistance are too intrusive, and that measures of physical activity such as wrist or head movement not sufficiently sensitive;
- some devices based upon measures of eye activity were considered to be suitable, depending on the way in which measures were taken, and those considered as potential candidate devices for further evaluation have been identified;
- few empirical studies have previously undertaken an independent comparison of actual devices;
- the use of model-based techniques to identify the increased likelihood of sleepiness is a promising approach, particularly when used in combination with other real time measures such as eye activity and steering wheel movements.

A subset of 15 devices was identified as potentially being worthy of subsequent evaluation. These included devices based on eye movements, driver behaviour (including steering and lane deviations), model-based, and on combinations of variables. These were as follows:

Devices based on eye movements:

- CoPilot
- ETS-PC Eye Tracking System
- faceLAB 2.0
- MTI AM eye
- Onguard
- Optalert

- PERCLOS
- Smart Eye
- APL Drowsy Driver System

Devices based on driver behaviour (including steering and lane deviations):

- DAS 2000 Road Alert System
- SAMG-3Steer
- SAFETRAC

Devices based on fatigue models:

- Sleep Watch

Devices based on combinations of variables:

- ASTiD (steering wheel movements and sleep history)
- SmartCar Driver Behaviour (contextual driving information and eye movements).

Further details of each device can be found in Appendix A in Tables A1-A5

The review also clarified the purpose of sleepiness detection devices. It emphasised that these devices were intended to warn drivers that their driving performance was likely to be compromised by reduced alertness, and were not intended to 'keep the driver awake'. In particular, within commercial driving settings, it was emphasised that driver scheduling should seek to ensure that the driver had sufficient opportunity within each day to obtain adequate sleep, and within driving periods had time available to take regular breaks. This approach was considered key to fatigue management for both commercial and non-commercial drivers, and the role of sleepiness detection devices should only be seen as a fall-back safety aid.

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Appendix A. Tables of devices

A.1 Physiologically-based devices

Name of device	Operational, validation, market and assessment status	Intrusiveness and likely operator acceptance	Format of warning or alert	Contact details of supplier
Physiological, physical, behavioural or model-based operation	***For example, in routine use, tested in lab, validated in operational setting, available commercially***	***Limitations on use, for example environmental noise or light; relevance to specified occupational settings***	***For example, auditory, visual or other***	***Details as at time of review, these may change***
AlertDriver Monitors eye droop, pupil occlusion and eye closure via a camera. Uses image neural nets, fuzzy logic to locate subject's eyes. Is also model-based	Not yet commercially available	Non-intrusive, is sited in front of face on the dash board. Sensitive to use of sunglasses, but works with prescription glasses and contact lenses	Auditory alarm warns of low alertness, defined as eyes closed for more than 1.5s or sustained pupil occlusion occurs. Alarm deactivated by eye opening or user-specified amount of time.	Future Technology and Health, LC PO Box 1233 337 E. College Street Iowa City Iowa USA Tel: 319/354-7652 E-mail:
CoPilot See also PERCLOS system upon which CoPilot is based. Detects percentage of time eyes are closed over a specified time interval (PERCLOS system) via infrared camera system	Is being evaluated in a variety of research settings including simulator and on-road scenarios. US Patent obtained, commercialisation is under negotiation	Non-intrusive. Operator does not wear any additional equipment. Current version limited to night-time use. Developer is currently extending system to operate under daylight conditions.	Auditory and visual stimuli. Different levels of warning depending on PERCLOS measures. Current system has only audible tone	Driving Research Centre, 10 40th Street Pittsburgh PA 15201 USA Tel: 412-681-7159 Fax: 412-681-6961 E-mail: rgrace@rec.ri.cmu.edu

Name of device	Operational, validation, market and assessment status	Intrusiveness and likely operator acceptance	Format of warning or alert	Contact details of supplier
DaimlerChrysler Eye-Gaze Detection System Measures eye gaze via dashboard camera.	Is under development.	Non-intrusive.	No warning system	DaimlerChrysler AG Ulm, Germany
Expresseye Measures fixation, gaze control and saccadic eye movements to a target Uses infrared light corneal reflection technique	Available commercially	Highly intrusive head-mounted optics and so is only suitable for laboratory use. Is essentially a visual task Rather than a real time alertness assessment. Operates under normal room light conditions.	No warning system	Optomotor Laboratory c/o B.B.L. Fischer Tivolistraße 11 D-79104 Freiburg Germany Tel: +49 761 2922600 Fax: +49 761 2922699 E-mail: info@ optom.de
EyeHead Measures eye position, head position and eye to point of fixation distance Uses a magnetic head tracker	Prototype device used in research	Uses head-mounted optics so suitable only for laboratory use.	Not implemented	Ms. Virginia Salem Mr. Robert Baer Applied Science Laboratories 175 Middlesex Turnpike Bedford, MA 01730 USA Tel: (781) 275-4000 Fax: (781) 275-3388 E-mail: asl@a-s-l.com
Eye-Gaze System Measures gaze-direction via corneal reflection technique. Also measures pupil diameter, blinking, and eye fixation.	Is available commercially.	Requires head-set to be worn	Not implemented	LC Technologies, Inc 9455 Silver King Court Fairfax, Virginia 22031-4713 U.S.A. Tel: 703-385-7133 or 800-EYEGAZE (800-393-4293)

Name of device	Operational, validation, market and assessment status	Intrusiveness and likely operator acceptance	Format of warning or alert	Contact details of supplier
				Fax: 703-385-7137
Eyeputer Records eye movements via corneal reflection technique	Is used by NASA, European Space Agency, RENAULT, CNRS, CNES, Institute of Neurology (London) and Balard Hospital (Paris) for research.	Comprises a light headset attached to the head.	No warning system.	www.electronica.fr/alphabio alphabio@eletronica.fr
ETS-PC Eye Tracking System Detects eye closure via a camera	Available commercially and currently being used in research environment by car manufacturers	Non-intrusive. Operator does not wear any additional equipment. Manufacturer states that the system adapts to different lighting levels (operates in daylight and darkness)	No warning stimuli currently included	Ms. Virginia Salem Mr. Robert Baer Applied Science Laboratories 175 Middlesex Turnpike Bedford, MA 01730 USA Ph (781) 275-4000 Fax (781) 275-3388
FaceLAB 2.0 Measures eye-gaze and eye closure Uses PERCLOS fatigue assessment scale	FaceLAB2.0 system is now commercially available and is currently being used as a research tool. But not as an alertness device ?	Non-intrusive ? Is OK with day or night-time, and copes with both. Also OK with (sun) glasses. Copes with partial head occlusion.	No warnings in place (2004)	Seeing Machines Innovations Building Corner Garran and Eggleston Rd. Canberra Australia
IM-Blinkometer Detects blinks using a piezoelectric adhesive disk attached to canthus of the eye	Research device	Highly intrusive as requires detection of disk to canthus of eye. Requires calibration for individual subjects	No warnings	IM Systems 1055 Taylor Avenue, Suite 300 Baltimore, MD 2 1286 4 I O-296-7723
MTI AM eye Detects eye blinks. Measures ratio of closed to open eyes to detect	Research device	Requires the use of glasses.	Warning system designed to become increasingly urgent, initially comprising visual indicator, followed by an	Edward MacLeod MTI Research Inc. Chelmsford, MA (508) 250-4949

Name of device	Operational, validation, market and assessment status	Intrusiveness and likely operator acceptance	Format of warning or alert	Contact details of supplier
sleepiness Uses infrared reflectance			auditory tone and then a shaker alarm	
Nissan Drowsy/ Inattentive Driver Warning Uses image processing to monitor eyelid movements	Under development	Operates day and night Insufficient information to evaluate	No warning system developed.	Nissan Motor Corporation Communications Department 17-1, Ginza 6-chome, Chuo-ku, Tokyo, 104-8023 Japan Tel: +81-3-5565-2147
Onguard Measures eye closure, activates an alarm after 0.5s closure period. Uses infrared reflectance.	Is a prototype device	Is obtrusive due to requirement to wear adapted glasses	Auditory alert	Xanadu Israel
Optalert™ Uses infrared oculography to detect eyelid movements during blinking and eye closure. Is developing system further to measure inter-saccade interval (may be more prediction of alertness, and also detect absence of changes in gaze	Currently being trialled in truck and car drivers within Australia, Asia and Europe (e.g. BHP Australia; Denso, Japan; Siemens, France) during routine driving operations. Planned to be available commercially by July 2005	Operator must wear spectacles within which transmitter/receiver is mounted. Potentially can be mounted within users' own (prescription) glasses May require validation for individual differences, e.g. differently shaped eyes. Operates in darkness or daylight	Auditory stimuli. Proposes a two stage warning system comprising 1. warning of potential drowsiness and 2. critical drowsiness (details unspecified)	Dr M Johns, Sleep Diagnostics Pty Ltd, Chestnut St Richmond Melbourne VIC 3121 Australia

Name of device	Operational, validation, market and assessment status	Intrusiveness and likely operator acceptance	Format of warning or alert	Contact details of supplier
PERCLOS Detects eye closure using infrared, retinal reflectance device. Measures duration of blinks and eye closures, and proportion of time eyes closed over a specified time interval.	Is being brought to market by Attention Technologies Inc. through the CoPilot system. Is being evaluated by a trucking company along with Sleep Watch and SafeTrac.	Image analysis – non-intrusive Problems with detecting eye closure during night driving	Provides continuous green-amber-red warning light to indicate sleepiness level, accompanied by auditory tone when critical level detected (quoted as 3-4s eye closure)	WW Wierville & Richard Grace Carnegie Mellon Research Institute Carnegie Mellon University 5000 Forbes Avenue Pittsburgh, PA 15213 Tel: 412-268-2000
Photo Driven Alert System Worn on ear and measures blink rate.	Under development in motor vehicles	Requires device to be worn on ear and so is intrusive. Is also incompatible with wearing glasses	Auditory alert	Michael Myronko 117A Northgate Basford Nottingham UK
SafetyScopeTM Ocular system in quantifying sleepiness.	Commercially available	Head-mounted system	No warnings implemented	Eyedynamics WWW URL www.eyedynamics.com
Smart Eye Detects head position and point of gaze via image processing	Commercially available	Non-intrusive	No warnings described	Smart Eye AB Stora badhusgatan 18-20 411 21 Göteborg, Sweden Phone: +46 (0)31 339 32 30 Fax: +46 (0)31 339 30 31 E-mail: info@smarteye.se

Name of device	Operational, validation, market and assessment status	Intrusiveness and likely operator acceptance	Format of warning or alert	Contact details of supplier
Toyota Driver Drowsiness Detection and Warning System Detects eyelid movement using camera mounted on rear-view mirror.	Prototype system under research	Non-intrusive	Acoustic warning. Provides warning through an in-vehicle navigation system	Toyota Motor Corporation Public Affairs Division, ITS planning Division 1 Toyouta-Cho, Toyouta shi, Aichi Prefecture 471-8571, Japan, Tel: 81-565-28-2121
Vehicle Drivers Anti-Dozing Aid (VDAD) Measures eye closure and head movement via infrared reflectance. Developed by US military.	Research application	Worn on ear and attached by a headband. Likely to interfere with wearing of glasses	Three different alerting mechanisms: 1. vibrator (on temple) 2. acoustic tone 3. random pressure pulsed applied to temple via carbon dioxide cartridge	BRTRC Technology Research Corporation 8260 Willow Oaks Corporate Drive Suite 800 Fairfax USA www.brtrc.com

Name of device	Operational, validation, market and assessment status.	Intrusiveness and likely operator acceptance	Format of warning or alert.	Contact details of supplier
ABM Drowsiness Monitoring Device (DMD) Records EEG via telemetry to detect drowsiness	Has US patent. Production model is obtainable commercially. No information on validation of the EEG algorithm	Too intrusive. Requires operator to wear baseball cap containing electrodes. Uses disposable electrodes. No information about the EEG algorithm.	Auditory alert when EEG-determined drowsiness indicator exceeds threshold	Advanced Brain Monitoring Inc 2859 Pio Pico Drive, Suite A Carlsbad California USA
EEG Based Algorithm to Detect Different Levels of Driver **Fatigue** Uses delta, theta, alpha and beta activity of the EEG to detect 'early, medium and late' sleepiness	Under development via field research	Electrode and wireless technology under development	No warning system	Dr Sara Lal University of Technology, Sydney Health Sciences Building 1, L 14 Broadway, 2007 Australia Tel: 612 95141592 Fax: 612 95142228 E-mail: sara.lal@uts.edu.au
Engine Driver Vigilance Telemetric Control System 3rd generation (EDVTCS) Measures electrodermal activity and electrodermal reactions. No information on specific parameters	In routine use on Russian railways. However no validation or device performance data is available.	Operator required to wear wrist-worn sensor containing sensor. Skin resistance measures affected by factors other than drowsiness, e.g. stress, sweating, emotions	Auditory alarm activated when alertness falls below critical level. If not cancelled, brakes are applied	J-S Co. Neurocom 423, rue de Clausen Luxembourg BP 531 Phone: +352 42 31 18 Fax +352 42 16 80

A.2 Physical including wrist activity and head movements

Name of device ***Physiological, physical, behavioural or model-based operation***	**Operational, validation, market and assessment status** ***For example, in routine use, tested in lab, validated in operational setting, available commercially***	**Intrusiveness and likely operator acceptance** ***Limitations on use, for example environmental noise or light; relevance to specified occupational settings***	**Format of warning or alert** ***For example, auditory, visual or other***	**Contact details of supplier** ***Details as at time of review, these may change***
Actiwatch-alert Measures wrist inactivity associated with sleep	Device evaluated in aircrew flying routine civil air operations, and principle evaluated in two additional airline operations	Wrist-worn accelerometer. Non-intrusive, and rated as acceptable by aircrew in experimental study carried out during routine operations Aviation, shipping application rather than driving	Auditory warning activated after 4-5 minutes inactivity, which is cancelled by pilot	Cambridge Neurotechnology Ltd. Cambridge UK
Doze Alert Measures head-tilt as sleep occurs	Available commercially	Is worn on ear. Can be worn with glasses.	Auditory warning	SAV-A-LIFE Industries LTD. New York Tel: 1-800-654-3337 Website: www.sav-a-life.com
Driver Alert Warning Device Measures head-tilt via pressure device on neck	Available from the AAA.	Non-intrusive. Pressure sensor below chin, attached via loose loop	Auditory warning	Slarner
EPAM Measures wrist inactivity associated with sleep	Being evaluated by an Asian airline	Non-intrusive	This device emits a beeping sound when inactivity lasts more than the pre-specified maximum duration.	No information available
MINDStim (MicroNod Detection System)	Device patented. Tested in lab-based research	Overhead plate containing capacitive sensing system.	Visual warning followed up by an auditory signal,	Advanced Safety Concepts, Inc (ASCI)

Name of device	Operational, validation, market and assessment status	Intrusiveness and likely operator acceptance	Format of warning or alert	Contact details of supplier
Monitors head movements. Learns typical patterns of movement, and detects those associated with drowsiness	No validation information available.	Non-intrusive, although the device may have safety implications, for example, in a crash situation. Also time taken to detect drowsiness onset unspecified Operates within normal background noise. Sensor plate must be horizontal. Can be retrofitted to vehicles	to be cancelled by driver	227 East Palace Avenue Suite 0 PO Box 2538 Santa Fe NM87504 tel: 505-984-0273 Fax: 505-984-3269
Proximity Array Sensing System (PASS) Detects brief head movements associated with sleepiness. Uses system of electromagnetic field. micro sleeps.	Prototype available for research	Susceptible to interference. Potential safety hazard due to radiation.	No information on warnings available	Advanced Safety Concepts, Inc (ASCI) 227 East Palace Avenue Suite 0 PO Box 2538 Santa Fe NM 87504 Tel: 505-984-0273
StayAlert Detects head droop by detecting chin contact with device worn round the neck	Product has US and international patent.	Non-intrusive	Provides auditory, visual and tactile warnings	Richard Bang Good One Inc. 3200 Wilshire Blvd. North Tower Ste 1388 Los Angeles, CA 90010 Tel: 213 383-9150 Fax: 213 383-9180

A.3 Behavioural including driver/operator performance and response time to secondary task

Name of device ***Physiological, physical, behavioural or model-based operation***	**Operational, validation, market and assessment status.** ***For example, in routine use, tested in lab, validated in operational setting, available commercially***	**Intrusiveness and likely operator acceptance** ***Limitations on use, for example environmental noise or light; relevance to specified occupational settings***	**Format of warning or alert** ***For example, auditory, visual or other***	**Contact details of supplier** ***Details as at time of review, these may change***
ARRB/ACARP Device for Monitoring Haul Truck Operator Alertness Uses a secondary task to estimate alertness via a auditory and visual reaction time task (tailored to individuals). Used in mining industry trucks	Currently is a prototype	Is a secondary task, and can be used as 'fitness-for-duty' test Is performed frequently while on shift.	Warning alert provided to driver and shift supervisor	3.2.2.5 Developer Contact Details ARRB Transport Research Ltd 500 Burwood Highway Vermont South Victoria Australia
DAS 2000 Road Alert System Measures drivers' acceleration, braking, gear changing, lane deviation and distances between vehicles.	Available commercially	Non-intrusive	Detects and warns of centre-line or hard-shoulder crossing via auditory tone	The Market Place Tel: 913-271-1840 www.premiersystems.com/market/

Name of device	Operational, validation, market and assessment status	Intrusiveness and likely operator acceptance	Format of warning or alert	Contact details of supplier
EICAS (Engine Indication and Crew Alerting System) Monitors aircrew interactions with aircraft (communications, Flight Management System and ATC annunciations). Warns if no activity detected within specified time (usually 20min)	Installed on Boeing long-haul aircraft	Non-intrusive and no limitations on use	Warning beep emitted to indicate low pilot activity. If no response then further auditory alert activated (options are and synthesized tones)	Dr Curt Graeber. Boeing, Seattle, USA (installed by Rockwell Collins www.rockwellcollins.com)
FMD – Fatigue Monitoring Device Is auditory and visual reaction time test Response pads on steering wheel Used in mining trucks	Has been evaluate in mining trucks. Is also being tested in trials with livestock carrier trucks	Sensitive to variations in workload. Developed as fitness for duty test	Auditory tone activated if reaction time 3 standard deviations longer than individual's nom. Results transmitted to base station	Developer Contact Details Attention Technology Tel: (412) 3410583
Health and Usage Monitoring System (HUMS) Monitors pilot interactions with aircraft. Uses inactivity interval exceeding preset duration to indicate sleep	Prototype unit under development for use in aerospace industry	Used by a number of aerospace companies		P.O.Box 1980 Halfway House, 1685 South Africa Tel: +27-11-695-7544 Fax: +27-11-315-1645 E-mail: marketing@ams.co.za www.ams.co.za

Name of device	Operational, validation, market and assessment status	Intrusiveness and likely operator acceptance	Format of warning or alert	Contact details of supplier
Roadguard Is a secondary task comprising a reaction task. Only operates when vehicle is in top-gear	Prototype under development	Intrusive as is secondary task	Auditory alarm	
Safety Driver Advisor Learns normal driver steering movements and detects deviations from normal Comprises a driving time measure, a dashboard display of recommended rest-break times and a monitor of erratic steering behaviour. Recommended driving time is 2h for day, 1h for night	No information available	Potentially poorly designed warning system	Audio-visual display activated and requires driver to stop vehicle in for a break in order to cancel auditory warning	Nissan Motor Corporation Communications Department 17-1, Ginza 6-chome, Chuo-ku, Tokyo, 104-8023 Japan
SAMG-3Steer Monitors normal corrective movements of steering wheel	Being tested in several UK trucking companies. No information on validation	Non intrusive. No equipment worn by operator. Can be switched off when use inappropriate (reversing etc)	Auditory tone, audible above road noise	Electronic Safety Products, Inc. 5410 Rock Hampton Court Indianapolis, Indiana 46268 Tel: 800-683-6654 Fax: 317-471-4142

Name of device	Operational, validation, market and assessment status	Intrusiveness and likely operator acceptance	Format of warning or alert	Contact details of supplier
Stay-A-Wake monitors speed and steering behaviour	Under development	Poorly designed warning system likely to cause startle	An alarm sounds if no steering movements (reversals or advancements) are made within a three to seven second period. If warning ignored cruise control is disabled and vehicle's horn activated	Developer Contact Details Reli Corporation of Markle Indiana
Travalert Monitors steering wheel patterns, via sensor on steering shaft	No information available	Non-intrusive	Auditory alarm if abnormal. steering patterns; sound level increases (to max of 110dB)	TravAlert Safety International, in Margate, Florida, USA
SAFETRAC Uses measurement of lane deviations and steering movements	Is being evaluated by several trucking companies. Available commercially as a windshield mounted camera and a driver interface that attaches to dashboard. System interfaces via cigarette lighter.	Non-intrusive. Operates in most conditions including strong sunlight, rain and snow. Lane tracking in night time rain is problematic (system warns driver of this problem via auditory signal)	Auditory and visual warnings activated when sleepiness indicated	AssistWare Technology, Inc. Todd Jochem; Dean Po merleau 12300 Perry Highway Wexford PA 15090 Tel: 724-934-8965 Fax: 724-934-8949 E-mail: toddj@assistware.com; deanp@assistware.com www.assistware.com

A.4 Model-based using predictions from prior sleep, circadian factors and work patterns

Name of device ***Physiological, physical, behavioural or model-based operation***	**Operational, validation, market and assessment status** ***For example, in routine use, tested in lab, validated in operational setting, available commercially***	**Intrusiveness and likely operator acceptance** ***Limitations on use, for example environmental noise or light; relevance to specified occupational settings***	**Format of warning or alert** ***For example, auditory, visual or other***	**Contact details of supplier** ***Details as at time of review, these may change***
Fatigue Audit Interdyne System (FAID) Mathematical model based on work/rest patterns.	Product is available commercially.	Non-intrusive. Fatigue scores are predicted before journey. None identified. Individual differences require investigation	No alarms or warnings Output comprises hourly fatigue score	Inter*Dynamics* Pty Ltd Sydney Office +61 2 9975 6925 Brisbane Office +61 7 3229 8300 Adelaide Office +61 8 8211 9933
Sleep Watch Determines amount of sleep taken using wrist-worn accelerometer, and predicts and displays level of alertness on watch	Is being tested by several long-haul trucking companies.	Non-intrusive. No limitations identified. But does not predict actual sleepiness, rather the probability of sleepiness	Two models, one with auditory feedback, other with visual feedback. Is not an alert, rather continuous feedback.	Ambulatory Monitoring Inc (AMI) 731 Saw Mill River Road, Ardsley NY 10502-0609 Telephone: 800 341-0066 Fax: 914 693-6604
US Army's Sleep Management System (See Sleep Watch also) Mathematical model based on work/rest patterns over last month and circadian influences to predict impaired performance	Validation by American Trucking Association Foundation and Federal Motor Carrier Safety Administration. Developed commercially as 'Sleep Watch'	Non-intrusive. Individual differences require investigation.	Not implemented	Walter Reed Army Institute of Research (WRAIR) USA

A.5 Combined the use of more than one approach

Name of device ***Physiological, physical, behavioural or model-based operation***	**Operational, validation, market and assessment status** ***For example, in routine use, tested in lab, validated in operational setting, available commercially***	**Intrusiveness and likely operator acceptance** ***Limitations on use, for example environmental noise or light; relevance to specified occupational settings***	**Format of warning or alert** ***For example, auditory, visual or other***	**Contact details of supplier** ***Details as at time of review, these may change***
Advisory System for Tired Drivers (ASTiD) Uses model based on time of day, the quality of the driver's sleep in the last 24h, total driving time and monotonous conditions. Is combined with patterns of steering wheel movements, computes fatigue on a display panel	Currently being evaluated by field studies in several long-haul companies in the UK and other countries	Non-intrusive. No limitations	Continuous indication of fatigue. Visual and auditory warnings, instructs driver to have a break, based on a preset level of fatigue	Loughborough Sleep Research Centre University of Loughborough UK Pernix ltd 1 Abbots Quay Monks Ferry Birkenhead Wirral CH41 5LH
APL Drowsy Driver Detection System (DDS) Uses doppler radar to measure speed, frequency, duration of eyelid closure, heart rate and respiration. Sleepiness based on general activity and eye activity monitoring.	Currently used for research US patent issued	Records data under all driving conditions, including bright sunlight, darkness and rain. However, with the exception of eyelid activity, the physiological measures are relatively insensitive and non-specific to sleepiness.	Warnings not described and no evidence of their implementation	The Johns Hopkins University Applied Physics Laboratory 11100 Johns Hopkins Road, Laurel, MD. 20723-6099 USA Tel: 240-228-5000 Fax: 240-228-1093

Name of device	Operational, validation, market and assessment status	Intrusiveness and likely operator acceptance	Format of warning or alert	Contact details of supplier
COMPTRACK Uses EEG frequency analysis and secondary (tracking) task	Research based	Requires a secondary task, and use of EEG electrodes	Not implemented	Institute for Neural Computation University of California San Diego 0961 La Jolla CA 92093-0961 (858) 458-1927 x11 (858) 458-1847 fax
Sensewear Pro Combination of measures of activity via accelerometers, skin temperature and near-body temperature. Detects sleep with 95% accuracy	Available commercially Is currently a research tool	Is worn on the arm with sensors housed within a band. Likely to be Insensitive to sleepiness	No warning system described	Body Media Smithfield Street 12th Floor Pittsburgh PA 15222 USA Tel: 412.288.9901 Fax: 412.288.9902 E-mail: info@bodymedia.com www.bodymedia.com

Name of device	Operational, validation, market and assessment status	Intrusiveness and likely operator acceptance	Format of warning or alert	Contact details of supplier
SmartCar Driver Behaviour Uses cameras to capture traffic information outside, and inside to detect head position. Synchronized with data acquisition from braking, gear changes and steering. Gaze direction measures by camera mounted on glasses pair of glasses .	Is a prototype device under development	Driver must wear glasses for the gaze direction monitoring.	No warning system described	Nuria Oliver/Alex P. Pentland Media Laboratory Massachusetts Institute of Technology (MIT) 20 Ames St E15-385 Cambridge MA 02139 Ph: 617 253 0608 - Fax: 617 253 8874
Wearable Alertness Monitoring Guard Detects eyelid closure via image analysis, reaction time, head movement and heart-rate	Being developed for industrial environments	Helmet-mounted, suitable for industrial and military applications Suitable for hazardous environments where head protection is worn, such as industrial and military contexts	Visual and audible alarm	Gerald Kaefer Graz University of Technology, AUSTRIA kaefer@iti.tugraz.at