NATIONAL ROAD TRANSPORT COMMISSION

REVIEW OF FATIGUE DETECTION AND PREDICTION TECHNOLOGIES

September 2000

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Abstract:	This report reviews existing fatigue detection and prediction technologies. Data regarding the different technologies available were collected from a wide variety of worldwide sources. The first half of this report summarises the current state of research and development of the technologies and summarises the status of the technologies with respect to the key issues of sensitivity, reliability, validity and acceptability. The second half evaluates the role of the technologies in transportation, and comments on the place of the technologies vis-a-vis other enforcement and regulatory frameworks, especially in Australia and New Zealand. The report authors conclude that the hardware technologies should never be used as the company fatigue management system. Hardware technologies only have the potential to be a last ditch safety device. Nevertheless, the output of hardware technologies could usefully feed into company fatigue management systems to provide real time risk assessment. However, hardware technology output should never be the only input into a management system. Other inputs should at least come from validated software technologies, mutual assessment of fitness for duty and other risk assessments of work load, schedules and rosters.
Purpose:	For information: to provide an understanding of the place of fatigue detection and prediction technologies in the management of fatigue in drivers of heavy vehicles.
Key words:	fatigue, road safety, fatigue detection, fatigue prediction, research.

FOREWORD

The National Road Transport Commission (NRTC) is responsible for making recommendations to the Australian Transport Council on initiatives to improve the safety of road transport and the uniform or consistent regulation of road transport in Australia.

A key part of the NRTC's work over recent years has been the development in conjunction with Australia's transport agencies and the road freight industry, of more nationally consistent regulations for the management of heavy vehicle driver fatigue. These regulations have now been introduced in New South Wales, Victoria, Queensland, South Australia and Tasmania. Western Australia and Northern Territory, which have traditionally not tightly regulated driving hours, have now adopted an approach to managing fatigue based on Codes of Practice under occupational health and safety legislation

The new national regulations provide some scope for operational flexibility in exchange for requiring transport companies and drivers to demonstrate a greater commitment to manage driver fatigue, however they are still heavily prescriptive and do not take fully into account the principles of fatigue research. Accordingly, the NRTC, with the support of agencies and industry, has commenced a review of regulatory approaches to heavy vehicle driver fatigue.

As part of this project, a review of fatigue detection and prediction technologies was commissioned. The purpose of the review was to inform participants in the policy development process of the potential role of fatigue detection and prediction technologies in the management of fatigue in drivers of heavy vehicles.

SUMMARY

This report reviews existing fatigue detection and prediction technologies. According to Dinges and Mallis (1998) different operator centered fatigue detection technologies can be classified as falling into one of four groups, these are:

1. Readiness-to-perform and fitness-for-duty technologies
2. Mathematical models of alertness dynamics joined with ambulatory technologies
3. Vehicle-based performance technologies
4. In-vehicle, on-line, operator status monitoring technologies

Data regarding the different technologies available were collected from a wide variety of worldwide sources. The first half of this report summarises the current state of research and development of the technologies and summarises the status of the technologies with respect to the key issues of sensitivity, reliability, validity and acceptability. The second half of the report evaluates the role of the technologies in transportation in 2000, and comments on the place of the technologies vis-a-vis other enforcement and regulatory frameworks, especially in Australia and New Zealand.

A fundamental problem confronting all of the technologies is their validation. As Dinges and Mallis (1998) indicate there are two aspects to the problem:

- what to validate the technology against (what is the criterion variable?)
- and the adequacy of the validation data (what is acceptable validation, what is the safe level of the fatigue index?).

The present authors are cautious about the choice of criterion variable for validation. Often this is a psychomotor or vigilance task. There were no validation data available drawn from on road behaviour or from crashes. We failed to find adequate data for many technologies, and only for a handful were adequate data available, although not drawn from on road behaviour or crashes. These data need to be collected before any technology could be considered for licensing for mandatory use.

The report distinguishes between hardware technologies which are aimed at detecting fatigue in real time, and software technologies which are aimed at predicting fatigue in the future based on past work and rest. The two technologies clearly have different validation requirements. The basis for the wide range of technologies considered in the report is in what they measure to index fatigue. Some measures are more plausible indexes of fatigue than others are. A convincing case has been made that slow eye lid droop (PERCLOS) has the best potential to detect fatigue. Only one commercially available software technology was reported and the predictive validity of that technology was not high.

The first half of the report concludes that some of the technologies are promising but that a great deal more work needs to be done in validating them.

The second half of the report examines the wider context of the use of the technologies. The problem of the choice of criterion variable for validation of the test is examined, along with the problems of integrating the output of the technologies into the transport system and whether they will receive acceptance. For example, fatigue detection is going to have to be considerably more accurate than drivers' own self reports if it is going to be relied upon by

drivers to improve safety. If it is less accurate than drivers' self reports then they will ignore it. This problem has serious implications for the integration of hardware fatigue technology into the industry. If drivers do learn to rely heavily on the technology because they believe it is accurate, then a technological failure could be catastrophic for the driver. These sections also raise many serious problems about the use to which the technology will be put and which will have to be addressed before fatigue technologies can be mandated.

The final sections of the report are concerned with how the technologies will sit alongside a regulatory regime and the conclusion is that they will complement the regime. They will require a different form of enforcement to the present regime and would most easily be enforced under occupational safety and health legislation.

A fundamental framing question throughout the report is: "how will the technologies be used- as safety devices or management systems?" It is the conclusion of the present authors that the hardware technologies should **never** be used as **the** company fatigue management system. There will be a strong temptation for companies to use them as management systems. Hardware technologies only have the potential to be a last ditch safety device. Nevertheless, the output of hardware technologies could usefully feed into company fatigue management systems to provide real time risk assessment. However, hardware technology output should **never** be the only input into a management system. Other inputs should at least come from validated software technologies, mutual assessment of fitness for duty and other risk assessments of work load, schedules and rosters.

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1. INTRODUCTION

Over the past ten years there has been an increased interest in technologies and procedures to monitor or reduce driver fatigue. Development of these technologies has taken place primarily in the USA and only secondarily in Europe and Australasia. Largely this interest has been brought about by the developers of such technologies, government agencies, and consumers eager to purchase a simple and effective countermeasure. As such, there is a movement towards widespread use of systems that may or may not detect fatigue (Dinges & Mallis, 1998; Mallis, 1999). It is therefore essential that such systems are properly developed and validated and that critical reviews of new technologies (such as the one in this report) take place.

Brown (1997), when considering the prospects for technological countermeasures against fatigue, argued that there were three main reasons why such technologies should be developed:

i. Fatigue is a persistent occupational hazard for professional drivers

ii. Some of these drivers are under considerable pressure to reach their destinations, despite feeling drowsy

iii. Fatigue adversely affects a driver's ability to assess his or her own fitness to continue driving.

However, he argues for some caution to be applied to the implementation of such fatigue countermeasures for two reasons:

i. Their reliability in real traffic conditions is largely unproven

ii. They could be used by unscrupulous drivers [or employers] to support the continuation of journeys that should have been finished because of impairment by fatigue.

This latter point has also been echoed by many other researchers in the area (eg Dinges and Mallis, 1998; Haworth, 1992). However, as Dinges and Mallis observe:

> *"…but a technology that can potentially enhance safety and save lives should not be prejudged based on speculations about users' ethics, whether realistic or exaggerated (for example, most motor vehicles can be accelerated to dangerous speeds, but the fact that some drivers elect to speed is not used to justify placing acceleration governors on motor vehicles. Rather, education and laws exist to teach drivers how to properly use the acceleration potential of a motor vehicle)."* (Dinges and Mallis, 1998, page 210).

When considering the use of fatigue monitoring technologies, there should be a guarantee that the validity, reliability, generalisability, sensitivity and specificity of the system have been thoroughly tested and reported (or at least be available). These criteria are defined and summarised in Table 1 below.

Table 1: Definitions of scientific criteria adapted from Dinges and Mallis (1998).

Validity	Does it measure what it purports to measure (operationally and conceptually)?
Concurrent Validity	The extent to which one variable predicts another at the same point in time; can one variable be used to predict the other at the same point in time?
Predictive Validity	The extent to which one variable predicts another variable at some point in the future; can one variable predict the other at some point in the future?
Reliability	Does it measure the same thing consistently?
Generalisability	Does it measure the same events in everyone?
Sensitivity	How often will the device miss detecting a fatigue event or operator?
Specificity	How often will the device give an alarm that is false?

Similarly, Haworth (1996) summarising other research, stated that such technologies (at least, when in-vehicle) must be capable of informing the driver of any deterioration in driving performance, operate in real time with little/no calibration, that the fatigue indicator must not disturb the driving process and that issues such as cost and compatibility with other systems are taken into account.

As will be seen below, most of the technologies currently offered are in the prototypic, evaluation or early implementation stages, and as yet remain scientifically and practically unproven (Dinges & Mallis, 1998). In addition to developing the technology, wider factors and questions must be taken into account for successful implementation of such systems, these questions include:

- Who gets access to the fatigue detection results? Purely the operator? The employers? Or even wider, enforcement authorities (eg the police) (Dinges and Mallis, 1998)?

- Should rewards be given for non-fatigued driving (or conversely penalties for fatigued driving)?

- For in-vehicle technologies (either driving performance or condition of the driver), how should the results be displayed to the driver? As will be seen below, many systems solely adopt a warning tone or signal when the fatigue detected reaches a predefined level, but many questions are not answered by this approach. For example should the warning be auditory or visual? Will it increase driver workload? Will the fatigue warning be followed? When should it be presented (as some evidence suggests that an alerting signal is only effective for approximately one minute after it is presented)? One interesting approach to this issue is the use of an 'alertometer' (Knipling, 1999), where alertness monitoring is viewed as a performance feedback system (similar to a vehicle's speedometer) rather than a warning system of an imminent collision.

- On a more conceptual level, what are most devices measuring anyway (Dinges and Mallis, 1998)? Most of the technologies do not specifically answer this question. Candidates include: vigilance, attention, alertness, microsleeps, hypovigilance, performance variability or vulnerability to error. The predictive relationship of these variables to crashes is usually unknown.

Addressing such issues is outside the scope of this report, however, considerations of these questions (and similar questions) will become critical for the successful future implementation of fatigue detection systems.

Several authors are concerned about the use to which the technologies may be put (e.g. Dinges and Mallis, 1998). A useful frame for viewing the technologies is to ask the question "*what are they used for?*" Is the technology to be used as a **safety device** such as a real time system providing the driver with instant feedback warning of imminent danger of falling asleep at the wheel? Or is the technology to be used as a **management system** (e.g. a corporate and individual driver's system which proactively manages driver work schedules, and promotes management of the amounts of rest and sleep drivers obtain, and therefore ensures the likelihood of driver alertness)?

The answer to this question has very different implications for how we evaluate the technology in a broader context. One technology might be useful as a safety device but a poor management system. Conversely another technology might be a useful management system but a poor safety device. A technology focusing on the present state of the driver is probably best used as a safety device, although information so gained could inform management systems if used intelligently. A technology focusing on the future state of the driver might be best used as a management system. These are important issues so the benefits and dangers of using each technology as a safety device or management system will be discussed in the later sections of the report.

The first half of the report is concerned with providing an overview of what technologies are available, what information we have on each technology and how these technologies perform against the criteria in Table 1 based on the available information. The second half of the report is concerned with the problems of evaluating the technologies according to how the technology could be used – safety device or management system. It is also concerned with how its use could benefit or impair transportation safety. Given the paucity of information and research on the performance of the technologies the second half of the report is speculative but it raises important questions which need answers before the technologies are introduced into transportation.

2. FATIGUE DETECTION TECHNOLOGIES

There are 4 classes of fatigue detection and prediction technology identified by Dinges and Mallis, (1998): 1. Readiness-to-perform and fitness-for-duty technologies; 2. Mathematical models of alertness dynamics joined with ambulatory technologies; 3. Vehicle-based performance technologies; 4. In-vehicle, on-line, operator status monitoring technologies. For convenience we will sometimes refer to "Mathematical models of alertness dynamics joined with ambulatory technologies" as software technology although one of the mathematical models is joined with hardware technology. We will sometimes refer to the other three technologies as hardware technologies.

Using this classification system the different approaches will be summarised and the specific technologies will be discussed.

2.1 Readiness-to-perform and fitness-for-duty technologies

"Fitness-for-duty or readiness-to-perform approaches, which are becoming popular replacements for urine screens for drugs and alcohol, can involve sampling aspects of performance capability or physiological responses. Because these tests are increasingly becoming briefer and more portable, the developers are seeking to extend their use beyond prediction of functional capability at the start of a given work cycle (i.e., prediction of relative risk over many hours), to prediction of capability in future time frames (e.g., whether someone is safe to extend work time at the end of a shift or duty period)" (Dinges and Mallis, 1998) .

Fitness-for-duty systems attempt to assess the vigilance or alertness capacity of an operator before the work is performed. The main aim is to establish whether the operator is fit for the duration of the duty period, or at the start of an extra period of work. The tests roughly fall into one of two groups: performance-based or measuring ocular physiology. Table 2 summarises fitness-for-duty tests (adapted from Charlton & Ashton, 1998; and Mabbott et al 1999).

Table 2: Fitness-for-duty tests

Test name	Described by	Measure/s	Comments
Truck Operator Proficiency System	Stein, *et al.* 1990; Charlton & Ashton, 1998; Charlton & Baas, 1998.	Psychomotor test, Divided attention test, Part-task computer driving simulator installed in a trailer. These can be adapted for Australian/ New Zealand conditions.	Developed specifically for detecting truck driver fatigue. Successful validation reported. Been in service in the USA since 1992.
FACTOR 1000	Allen, Stein & Miller, 1990.	Critical Tracking Task (Eye-hand coordination task) based on CTT developed by Jex.	Concern over predictive validity of eye-hand coordination task for divided attention tasks (such as driving). Preliminary analysis showed incident rate was less than expected when test was used to assess fitness for duty.

Test name	Described by	Measure/s	Comments
ART90	Charlton & Ashton, 1998.	Computer-based test battery of 8 to 10 tests including; visual perception, reaction time, concentration, cognitive processing & personality.	Used widely in Europe and elsewhere. Predicted 66% of driving mistakes, 50% of conflicts and 68% of specific driving errors.
FIT^R 2000 Workplace Safety Screener	Simpson (1998, unpublished). PMI Inc. Rockville, Maryland, USA	FIT 2000 is a table top eye testing instrument that gauges fitness for duty by measuring involuntary eye reflexes via a 30 sec viewing test to detect performance impairment. Four oculo-motor measures- initial pupil diameter, latency and amplitude of pupil response and saccadic velocity.	Only 80% detection of 0.06 & 0.08% BAC alcohol impairment & only assessed 40% of subjects as high risk after 48 hours awake.
OSPAT	Simpson (1998, unpublished). Romteck, Perth WA..	Computer-based psychomotor hand-eye coordination test.	Similar to Critical Tracking Task (Factor 1000). Concern over predictive validity of eye-hand coordination task for divided attention tasks (such as driving). No relevant validation data.
Psychomotor Vigilance Test (PVT)	Dr. David Dinges, University of Pennsylvania	A 10 minute administration of visual reaction time testing via a hand held device.	Principally a research tool and used to validate several of the fatigue detection technologies but could be used to assess fitness.

In other industries such as mining, fitness-for-duty tests have become increasingly popular, as tests will detect impairment from a loss of sleep or through the intake of alcohol or other drugs. However, it must be noted that the operator's state will change during the course of duty after passing a fitness-for-duty test. In transport research Mabbott & Hartley (1998) found that half of the drivers who reported falling asleep at the wheel had adequate sleep (8 hours plus) through the appropriate night period. Thus some operators are obtaining adequate sleep yet still develop fatigue after a significant period of vehicle operation.

Some fitness-for-duty tests have, however, shown good concurrent validity. The '*Truck Operator Proficiency System*' has achieved good results in identifying drivers who have little sleep. This test has been used by traffic and public safety officers in the US State of Arizona to determine if a driver is too incapacitated by fatigue to continue, as yet with no reported legal challenges to its validity when a driver is removed from the driving task after failing the test (Charlton & Ashton, 1998). To our knowledge no formal predictive validity has been established so it is not known whether drivers who failed the test could continue to drive safely. However, the test has high face validity so it is believed that failing the test means the driver could not drive safely.

2.1.1 Summary

In the real world some transport operators report for the start of a shift with a sleep debt already accrued (as, of course, do some non-commercial drivers before they get behind the wheel). Effective fitness-for-duty tests could have a place in these circumstances. However, as Haworth (1992) points out, the general applicability of use of such fitness-for-duty tests is less than that of vehicle (and in-vehicle operator performance) tests as most pre-work testing is only applicable for truck or other commercial vehicle drivers- the majority of other road users (eg car drivers) would not be tested. Similarly, as most of the devices are not especially portable, it would be difficult to test the operator after several hours of his/her shift when fatigue levels might be higher.

Thus used alone, fitness-for-duty testing, in some circumstances, has the potential to detect the occurrence of existing fatigue impairment (and accordingly, the potential to detect fatigue-related incidents). Their concurrent validity is therefore potentially good. However, their predictive validity has not been established for fitness for duty 1,2 or 10 hours into a trip. Predictive validity needs to be established before they can be used to plan delivery schedules.

It is the assertion of the authors, however, that when used in conjunction with other fatigue monitoring devices, the benefits and applicability would be greater. However, it must be observed that such tests are being used in many places (eg Arizona in the USA) so they certainly have a role to play in transportation in 2000. As this type of fatigue detection test is usually performed before a shift (or in a work break) a single testing device at a freight terminal could be used to test drivers as they report for duty. Thus it needs no special apparatus in the vehicle, so does not impinge on the performance of in-vehicle systems (such as route guidance) and can fit in well with other regulatory/enforcement methods.

2.2 Mathematical models of alertness dynamics joined with ambulatory technologies

As Dinges and Mallis (1998) state “This approach involves the application of mathematical models that **predict** operator alertness/performance at different times based on interactions of sleep, circadian, and related temporal antecedents of fatigue (e.g., Åkerstedt & Folkard, 1997; Belenky *et al.*, 1998; Dawson *et al.* 1998). This is the subclass of operator-centred technologies that includes those devices that seek to monitor sources of fatigue, such as how much sleep an operator has obtained (via wrist activity monitor, defined below), and combine this information with a mathematical model that is designed to predict performance capability over a period of time and when future periods of increased fatigue/sleepiness will occur.”

Several mathematical models have been devised which may be capable of predicting the level of performance for an individual, based on past sleep and workload factors. These highly complex algorithms allow for individual patterns of sleep, work and rest to be entered into a system that will then show outputs describing how levels of performance will be affected by the individual’s sleep/work history. The key issue for these models is their predictive validity; do they accurately predict what they are said to predict? Is this information available in order to assess the models?

2.2.1 Fatigue Audit 'Interdyne' system.

The Fatigue Audit 'Interdyne' system was developed by the Centre for Sleep Research at the University of South Australia (see for example Dawson *et al.* 1998). It is a mathematical algorithm based on timing, recency and duration of work and rest periods. Its objective is to allow companies to assess and compare previous, current and possible future work schedules in terms of predicted work related fatigue (McMahon, 2000). This is achieved by inputting work start and end times for a shift system into the program (including shift start and end times for the previous 7 days, to assess recent work history and recovery). The output consists of relative fatigue scores (ranging from 'standard' to 'extreme') for each hour of the shift schedule; this allows comparisons of different shift schedules on an hour-by-hour basis (McMahon, 2000).

The product is commercially available in Australia (and elsewhere) from InterDynamics Pty Ltd, Adelaide. However, the present authors question certain features of the model, such as:

1. The real world predictive validation results of the model are, as yet, not convincing. Evaluation by Fletcher and Dawson (2000) found that predicted fatigue scores correlated quite poorly with performance data (coefficients~0.13) and only moderately with self-reported performance data (coefficients~0.25) for a group of locomotive drivers.

2. The model makes no allowance for inter-individual differences. For example, would a healthy 30 year old who was well practised on a task experience as much fatigue as a 60 year old with minor health difficulties such as apnoea, who was new to the job? At present the model treats fatigue in all individuals as being equal. Health and domestic problems, which disrupt sleep are potentially a major source of fatigue, and are not accounted for in the Interdyne system.

3. The model makes little allowance for job demand- although the model makes some allowance for task risk. The latter is of course, not identical to job demand (whether physical, cognitive or emotional). For example would a job such as a librarian experience as much fatigue as a lumberjack (physical), air traffic controller (cognitive) or social worker (emotional)? The model does not distinguish between levels of fatigue caused by different jobs except in terms of the outcome via task risk.

4. The model only accounts for about 5% of variance (R^2) in the performance data (Fletcher and Dawson, 2000), making the model of little practical use. That is, 95% of the change in operator fatigue is unaccounted for, presumably because it derives from sources other than the inputs to the algorithm.

2.2.2 The US Army's Sleep Management System

The US army sleep management system is another mathematical model based on work/rest periods and circadian cycles (see Belenky *et al.* 1998). U.S. Army medical researchers at Walter Reed Army Institute of Research (WRAIR) have developed a mathematical model to predict human performance on the basis of prior sleep (Belenky *et al*., 1996; Belenky, 2000). They integrated this model into a wrist-activity monitor based sleep and performance predictor system called "Sleep Watch." The Sleep Watch system includes a wrist-worn piezo electric chip activity monitor and recorder which will store up records of the wearer's activity and sleep obtained over several days. It then incorporates the measures with circadian periodicity variables into a stored sleep and performance predictive algorithm. At any point in time, the algorithm estimates how much in need of sleep the wearer is. The Sleep Watch, via wristwatch-like display informs the wearer about his/her state of alertness based upon the presumed need for sleep, or indicates his readiness to continue to conduct his/her job until the next opportunity for rest and/or sleep. The Sleep Watch system is based predominately on the amount of sleep obtained or not obtained, over the previous 3-4 days, and the prediction of performance is based upon preconceived relationships of quantity and quality of sleep to real time readiness to perform at a particular point in time.

The U.S. Army Sleep Watch system will be one of the Fatigue Management Technologies (FMT) in a large 2-year field trial sponsored by the Federal Motor Carrier Safety Administration and American Trucking Associations Foundation (FMCSA-ATAF) beginning in the U.S. and in Canada in October, 2000. (See further description of this FMT test later in the paper). At this point, this technology is considered to be in the adolescent stage, and is not yet ready for prime time applications. Therefore it is not a system these authors could recommend for consideration in the Australian or New Zealand transport industry at present.

2.2.3 The Three-Process Model of Alertness (by Åkerstedt et al)

The fatigue model of Åkerstedt and his co-workers (eg Åkerstedt and Folkard, 1997; Folkard, Åkerstedt, Macdonald, Tucker and Spencer, 1999) is a model for predicting alertness/ performance. The model is summarised as:

The model uses sleep data as input and contains a circadian and a homeostatic component (amount of prior wakefulness and amount of prior sleep), which are summed to yield predicted alertness (on a scale of 1 to 16) as well as performance on monotonous tasks. The model includes an identification of levels at which the risk of performance/alertness impairment starts, as well as prediction of sleep latency and time of awakening of sleep episodes. It is suggested that the model may be used to evaluate work/rest schedules in terms of sleep-related safety risk. (Åkerstedt and Folkard, 1997, page 115).

While the model has been extensively evaluated and redesigned it has certainly not been widely used by transport companies or commercial drivers to assess the safety and efficiency of their shift schedules. Furthermore, as pointed out by Folkard, Åkerstedt, Macdonald, Tucker and Spencer (1999) at the moment the predictions from the model are difficult to reconcile with trends in industrial accidents or injury risks. Unquestionably the model will be further refined in the future; however, for the moment its lack of commercial availability makes it of little use for the majority of drivers in Australia and New Zealand in 2000.

2.2.4 Summary

The accuracy of the fatigue algorithm is critical. As Dinges (1997) states, "a model that mis-estimates a cumulative performance decline by only a small percentage can lead to a gross miscalculation of performance capability and alertness over the course of a working week". So while such models show potential to easily predict fatigue in operators, a large amount of validation and possible 'fine-tuning' of the models are needed before their veracity can be fully accepted. At the time of writing there are few convincing real world predictive validation data on this technology.

As with the fitness-for duty testing described above, the Fatigue Audit Interdyne technology is performed before a shift and needs no special apparatus in the vehicle, so it does not impinge on the performance of in-vehicle systems (such as route guidance) and can fit in well with other regulatory/enforcement methods. By contrast the U.S. Army sleep watch system is "continuous" and operates continuously 24 hrs per day, including within the truck cab. Drivers may consult their sleep watch at any time to determine whether they need sleep or not. Thus this model has not only the potential to predict fatigue but also detect it.

All the models do have the potential to improve the design of shiftwork rosters and even in their present state of development they could provide useful advice to inexperienced supervisors responsible for roster design. The next generation of these models will need to take account of individual differences in susceptibility to fatigue including indications of differences in circadian physiology and periodicity and the degree of fatigue caused by different job demands.

2.3 Vehicle-based performance technologies

As Dinges and Mallis (1998) state "These technologies are directed at measuring the behaviour of the driver by monitoring the transportation hardware systems under the control of the operator, such as truck lane deviation, or steering or speed variability, which are hypothesized to demonstrate identifiable alterations when a driver is fatigued as compared with their 'normal' driving condition."

These technologies have a sound basis in research which has shown that vehicle control is impaired by fatigue. However, these technologies are not without their own problems. What for example, is 'normal' or safety critical 'abnormal' variability for these measures? What is the range of 'normal' variability of these measures in the driving population? Could a perfectly safe driver be classified as 'abnormal' on occasions, eg. score a false positive? How has the threshold of 'abnormal' driving behaviour been selected? With rare exceptions these questions are not answered in the product descriptions. Thus these technologies also fail to provide satisfactory answers to the problem of successful validation.

Generally such technologies involve no intrusive monitoring devices and the output relates to the actual performance of the driver controlling the vehicle, hence technologies in this group seemingly have a great deal of face validity, despite the absence of satisfactory information on concurrent and predictive validity.

Driver steering wheel movements are used as the most common indicator of fatigue impairment and are mainly assessed through the reduction in number of micro-corrections to steering, which are necessary for environmental factors such as small road bumps and crosswinds. When these micro-corrections lessen, the operator is defined as being in an impaired state (Petit *et al.* 1990). The Steering Attention Monitor (S.A.M.) is a commercial product currently priced at US $210 that monitors micro-corrective movements in the steering wheel using a magnetic sensor that emits a loud warning sound when it detects 'driver fatigue' by the absence of micro-corrections to steering. Driving steering wheel input monitors have been developed, evaluated and in some instances were even commercially available from certain motor manufacturers (eg Nissan, as described by Yabuta et al 1985; and Renault, as described by Artaud et al, 1994; and for trucks as described by Haworth, 1996). The main problem with steering wheel input monitors is that they do not really work very effectively, or at least only work in very limited situations (Lavergne et al, 1996). Such monitors are too dependent on the geometric characteristics of the road (and to a lesser extent the kinetic characteristics of the vehicle), thus they can only function reliably on motorways (Artaud et al, 1994). Thus the approach now being developed by Renault is to integrate steering wheel input data with a video of the driver's face (to monitor eye lid droop). This work is still being developed and evaluated (see below for the difficulties associated with monitoring eye lid droop in the discussion of PERCLOS).

Other technologies measure drivers' acceleration, braking, gear changing, lane deviation and distances between vehicles. One such system is the DAS 2000 Road Alert System that detects and warns drivers that they have inadvertently crossed the centre line or right shoulder lines (in the USA). If either line is crossed without using the turn signals, the computer automatically sounds an audio alarm to alert the driver. No formal evaluation of this system has been located. The product is available at www.premiersystems.com/market/. However as a very general statement, after reviewing such methods the Accident Research Centre at Monash University Australia (1997) did not recommend them on their own as driver fatigue measures.

The use of several different forms of measurement is attractive to identify fatigue because if one measure fails to detect low arousal, another measure might be expected to pick it up (Mabbott et al, 1999). Most of these multi-sensor or 'hybrid' combinations are still in the prototypic or developmental stage and are yet far from being scientifically validated (Dinges *et al.* 1998). For example, a system in the US by scientists from the Applied Advanced Technologies group is being developed as one component of the NHTSA's Intelligent Vehicle Safety System (Carnegie Mellon University, 2000). It aims to combine detection of eyelid movements with lane deviations and steering movements. As discussed the U S Federal Motor Carrier Safety Administration is collaborating with the American Trucking Associations Foundation to test the over the road benefits of combining several fatigue detection technologies including lane tracking. The latter system will be provided by a company called AssistWare Technology [www.assistware.com]. The system is called: SafeTRAC: Drowsy Driver Warning System. It is a Lane Tracker system that mounts a tiny video camera on the windshield of the vehicle, facing outward toward the highway. It looks for lane markings and other road features, and it "senses" the driver's level of alertness by watching for weaving or erratic steering over a short prior history (e.g., 5-10 seconds of immediately previous driving). The system can provide an audible alert, and/or a visual display of vehicle centering or displacement relative to the center of the lane. To our knowledge no validation data have been collected.

Another device is: ZzzzAlert Driver Fatigue Warning System manufactured by DrivAlert Systems, Inc. in Indianapolis, Indiana, USA. Web site: www.zzzzalert.com. The supplier's description is as follows: ZzzzAlert is a small computerized electronic device that monitors corrective movements of the steering wheel with a magnetic sensor. When normal corrective movements cease, within four seconds (setting is adjustable) driver is alerted by an audible alarm. The alarm is automatically reset as soon as normal steering motion is restored. Alarm can be mounted almost anywhere in the truck cab. We know of no validation data on this product.

Another truck or driver weaving detection system is: TravAlert® Early Warning System produced by TravAlert Safety International, in Margate, Florida, USA. The supplier's description of TravAlert® is as follows: It was developed to loudly notify a motor vehicle operator that he/she has lost attention to the proper steering. TravAlert® is automatically activated when the speedometer reaches 42 miles per hour (MPH). The Erasable Electrical Programmable Read Only Memory (EEPROM) receives data from the Steering Shaft Sensor relating to motion. If proper driving procedures are followed the alarm will remain silent. If the operator is not attentive to proper steering patterns for a preset delay period (4-13 seconds), the alarm will sound gradually, ramping up to 110 decibels. The system automatically resets when proper steering patterns are resumed. The EEPROM records each alarm allowing for a download of information including real time of alarm, duration of alarm, and total alarms. The system is in no way physically connected to the operator of the vehicle and is completely tamper resistant. We know of no validation data on this product.

The **S**ystem for effective **A**ssessment of the driver state and **V**ehicle control in **E**mergency situations (SAVE system) of Brookhuis, de Waard, Peters, & Bekiaris, (1998), is further developed and has undergone validity testing during 1998. This system is described by Mabbott et al (1999):

*"The SAVE Project (Brookhuis et al. 1998) is formally known as **S**ystem for effective **A**ssessment of the driver state and **V**ehicle control in **E**mergency situations. The aim of the SAVE project is to develop a prototype that will in real time detect impaired driver states and undertake emergency handling. This will be realised by instant detection of impairment, following which the driver will be warned, drivers in the vicinity will be warned, or if need be, the vehicle will be controlled automatically to the road verge."*

Table 3 summarises the components and measures that are employed by the SAVE system (from Mabbott et al, 1999).

Table 3: The components and measures of the SAVE system.

Components	Physiological measures	Vehicle measures	Environmental measures
Integrated monitoring unit (IMU)	Eyelid closure	Speed	Time of day
Human-machine interface (HMI)	Head position	Steering wheel angle	Whether it rains or not
Hierarchical manager (HM)	Grip force on steering wheel	Distance to a lead vehicle	
SAVE warning systems (SWS)		Lateral position	
Automatic control device (ACD)		Time to line crossing	

In SAVE a Principal Component Analysis to reduce the data is first conducted, then a Neural Network calculation is conducted to decide on impairment and finally Fuzzy Logic is carried out to arrange the HMI (Human Machine Interface). Currently, the system appears to be detecting around 90% of fatigue cases, suggesting good concurrent validity (Mabbott et al, 1999, quoting Brookhuis, personal communication) but there is no formal report on the evaluation of the validity of the system. The use of multiple inputs to a model to detect fatigue requires that the inputs are integrated. Multiple inputs do not increase the likelihood of false alarms but reduce them essentially by checking all inputs. At present this system is still a long way from being commercially available.

2.3.1 Summary

Reasonably simple systems that purport to measure fatigue through vehicle-based performance are currently commercially available, however, their effectiveness in terms of reliability, sensitivity and validity is uncertain (i.e. formal validation tests either have not been undertaken or at least have not been made available to the scientific community). More complex systems (such as SAVE) are undergoing rigorous evaluation and design, and seem potentially very effective, however they are not yet commercially available. Thus the authors cannot recommend any of the current systems for immediate use in transportation in Australia and New Zealand in 2000. Equally, until more complex systems are further developed and validated, it is difficult to speculate upon the role of such technologies vis-a-vis other enforcement and regulatory frameworks.

2.4 In-vehicle, on-line, operator status monitoring technologies

As Dinges and Mallis (1998) state "This category of fatigue-monitoring technologies includes a broad array of approaches, techniques, and algorithms operating in real time. Technologies in this category seek to record some biobehavioral dimension(s) of an operator, such as a feature of the eyes, face, head, heart, brain electrical activity, reaction time etc., on-line (i.e., continuously, during driving)."

As such, in-vehicle, on-line, operator status monitoring is simply the measurement of some physiological/biobehavioural events of the operator whilst in the act of operating the machinery.

2.4.1 Electroencephalograph Measures

Physiological aspects of humans are known to reflect the effects of fatigue or other forms of impairment (Grandjean, 1988). A large number of monitors have been developed. The Electroencephalograph (EEG) has been acclaimed as one of the most successful monitors, sensed via an array of small electrodes affixed to the scalp, and examining alpha, beta and theta brain waves to reflect the brain status, identifiable in stages from fully alert, wide awake brain, through to the various identifiable states of sleep (Mabbott et al., 1999). EEG monitors are, however, not very practical for in-vehicle use.

One such device that does not require such intrusive electrodes is the 'Mind Switch', currently being developed at the University of Sydney; instead it employs a (slightly less intrusive) headband in which the electrodes are embedded or positioned to make contact with the driver's scalp to monitor brainwaves (Scullion, 1998). However, it will be some time before a prototype is ready and the validity and practicality of the device can be established.

2.4.2 Ocular Measures

If it is accepted that almost 90% of the information used by drivers is visual (Knipling, Wang & Kanianthra, 1996) then technologies that measure eye closure, eye movements or ocular physiology would appear to be a very suitable method to monitor driver fatigue. The fundamental premise is that eye behaviour can provide significant information about a driver's alertness, and that if such visual/ocular behaviour can be measured then it would be feasible to predict a driver's state of drowsiness, vigilance or attentiveness with regard to the driving task (Cleveland, 1999).

A plethora of eye blinking, pupil response, eye closure or eye movement monitors have been developed to assess driver fatigue, most of these however, have only reached the stage of being tested in the laboratory/simulator as a kind of 'proof-of-concept'. Whether such techniques can be successfully employed in the vehicle in real driving conditions is still largely a matter for intensive research and development and on the road testing. The key issues for these devices is their concurrent validity; can they predict how drowsy a driver is now?

A wide-ranging, recent evaluation of techniques for ocular measurement as an index for fatigue was conducted by Dinges et al (1998; and Dinges and Grace 1998) in which the 6 techniques were compared: an eye closure rating (PERCLOS), two EEG algorithms (Consolidated Research Inc, EEG algorithm, and Dr. Makeig's EEG algorithm), a head position monitoring device (Advance Safety Concepts Proximity Array Sensing System) and two Eye blink monitors (MTI Research, Inc. Alertness Monitor, and IM Systems, Inc. Blinkometer). The results found that nearly all the devices showed potential for detection of drowsiness-induced hypovigilance in at least one subject or subset of subjects. However, only one technology produced results (both intra-subject and inter-subject) that correlated with the validation criterion variable (psychomotor vigilance task performance lapses). Thus while all technologies showed some promise, the most effective performer was the eye closure rating called PERCLOS. It should be noted that the validation was against the vigilance task and not against driving behaviour or crashes, which raises the question of the predictive validity of the vigilance task for crashes.

- *PERCLOS*

A (April, 1999) Federal Highway Administration technical meeting (*Ocular Measures of Driver Alertness)* was primarily about the potential for using PERCLOS to measure fatigue (Carroll, 1999). The invited speakers included Bob Carroll from FHWA, John Stern from Washington University, Duane Perrin from NHTSA, Walt Wierwille from Virginia Tech, Melissa Mallis and David Dinges from University of Pennsylvania, Dixon Cleveland from LC Technologies, Richard Grace from Carnegie Mellon, Christine Johnson from FHWA, Martin Moore Ede from Circadian Technologies and Harvard Medical School, Robert Lavine from George Washington University, Michael Russo from Walter Reed Army Institute, Bill Rogers from the American Trucking Associations and Ron Knipling from FHWA.

‘PERCLOS', an acronym derived from percentage of eyelid closure, is a slow eye lid closure when 80% of the pupil is covered. PERCLOS was found to be the best potential measure of fatigue drawn from a range of ocular variables studied at Duke University in the 1970s and at Virginia Polytechnic Institute and State University during the 1980s and 1990s. Fatigue was manipulated by sleep deprivation and the ocular variables included pupilometry, gaze, saccades, convergence, blinking etc.

Walt Wierwille reviewed the work at Virginia Tech in the 1980s and 90s on PERCLOS, which antedates the current research program. There has been considerable progress with PERCLOS (80% slow eye lid closure) and it clearly is the best of the potential ocular measures for assessing fatigue. The data are impressive. But Wierwille adopted a fairly cautious stance on using PERCLOS to measure fatigue, certainly on its own. He was in favour of combining it with performance measures (eg. Lateral lane deviation).

Dixon Cleveland reviewed the technology for measuring PERCLOS. There is now good technology for measuring PERCLOS non invasively from dashboard mounted cameras using infra-red beams to measure retinal reflection and a light emitting diode beam to give a corneal reflection with which to measure gaze direction (by measuring the vector between the pupillary and the corneal reflections). PERCLOS no longer has to be measured manually from videos (Federal Motor Carrier Safety Administration, 2000). However, the outstanding problem at the time of the conference was loss of image to measure PERCLOS when drivers look in their mirrors outside the view of cameras. Since then this problem has apparently been over come, although problems may remain with getting good quality retinal reflections from some eyes. It is worth pointing out, that PERCLOS works fairly well in the darkness of night, but not very well at all in daylight, because ambient sun light reflections off the windows and continually bouncing around the truck cab as the vehicle turns relative to the sun's rays, make it impractical to obtain retinal reflections of infra-red.

Another concern is that any system should not just keep sounding a warning every few minutes, which would irritate drivers and lead to them ignoring it. This, of course, is not specific to PERCLOS, as many other ocular/ psychophysiological monitors would have the same issue to overcome.

David Dinges reported correlations of between 0.8-0.9 between PERCLOS and lapses on the psychomotor vigilance task (PVT), which requires the subject to respond to a randomly appearing light on a computer screen by pressing a button (Dinges, Mallis, Maislin and Powell, 1998). A lapse on the PVT is defined as a failure to respond to the task in less than 500 msec. This correlation is considerably better than correlations between lapses on the PVT and self report of drowsiness. It is of some concern that this correlation gets substantially LESS the longer the hours of sleep deprivation. The correlation should get greater with more sleep loss because there should be more variability in the data (more vigilance lapses and more PERCLOS).

In short the data were reasonably convincing that PERCLOS is going to be of some use although it is suspected that the context will be an issue (see below). And it seems probable that PERCLOS will be available in a few years in vehicles. The reservation about context is as follows. If drivers have 3 minutes warning they are about to have a micro sleep what do they do with the truck? The ultimate proactive action on the part of the driver should be to immediately stop the truck for a short break in driving. Whatever the driver does during that break (e.g. have a short nap, drink caffeinated coffee, splash cold water on his face, or just go for a short safety inspection walk around the truck etc.) might only have a temporary effect before the impending fatigue state returns. There is not likely to be a truck bay to hand and drivers will be moved on by the Police if they park elsewhere. The response to this concern was that “countermeasures such as peppermint spray could be used”. Some delegates at the meeting were then concerned that drivers would rely on the system to drive even further with the risk they might do so until a catastrophic sleep intervened.

The other issue of concern was that if drivers are experiencing sufficient PERCLOS to trigger an alarm are they already fatigued beyond a safe limit? That is, are they exhausted already? Most reasonable people would be worried if their driver’s eyes were drooping shut. What should be the permissible safe level of PERCLOS to prevent crashes?

A third concern was that to date PERCLOS has only been validated against the psychomotor vigilance test (PVT) under conditions of sleep deprivation. There are very many studies which demonstrate that measures of vigilance are sensitive to sleep deprivation and even short lived fatigue during circadian physiology lulls. However, the relationship between measures of on line (real time) vigilance and real world crashes has not been investigated to the knowledge of the present authors. Thus the power of PERCLOS to predict or prevent crash likelihood is presently unknown.

PERCLOS might have a major role in preventing severe crashes fatal to the driver where the driver is inattentive for a prolonged period (5-10 secs) and takes no evasive action. However, they are very small in number compared to serious injury and property only crashes. Like alcohol, fatigue (often defined by proxy criteria) is involved in only a small percentage of all crashes and a very large percentage of the small number of fatal to the driver (and fatal to others) crashes.

The meeting was clearly divided between the sceptics (including some industry representatives) and the proponents of PERCLOS such as FHWA and David Dinges largely on grounds of practicability. In some restricted situations, such as driving on a closed open-cut mine site, PERCLOS would probably work well because it would be practicable for a driver to stop the truck quickly (or be stopped automatically) and have a relief driver take over. But it was not clear what the appropriate remedial action could be in the road transport industry. A second issue was that PERCLOS would not work well if the driver was moving his head around a lot nor would it work in broad day light. These problems could be overcome by micro video cameras on a spectacle frame, but there might be problems of acceptance.

A final issue is what the threshold of PERCLOS should be for taking action. Obviously there is a dimension of differing durations of slow eye lid closures that could be considered as candidates for taking action to alert the driver. The percentage of pupil covered by the eye lid is another variable to be considered in alerting the driver. These questions need to be empirically resolved and validated before PERCLOS can be considered operational.

To summarise: PERCLOS is showing considerable promise and will surely have a great deal more US research money spent on investigating it in the next few years. At present, however, commercial availability of this product/technique is several years away at best whilst real world concurrent validation data are collected and safety criteria determined.

- *Other Ocular Measures*

Other ocular measures were described by Russo et al. (1999) and the Federal Highway Administration (1999). Russo found that decreases in saccadic (brief rapid movement of the eye between fixation points) velocity and increases in pupil constriction latency correlated with increases in simulator crash rates during conditions of sleep deprivation. Also using a vehicle simulator, the Federal Highway Administration (Professor John Stern) found encouraging results (in terms of displaying an effect due to time-on task, time-of-day or accident rates) for the following measures: blink duration, partial eye closures (similar to PERCLOS) and saccade frequency (and to a lesser extent blink frequency). However, as with PERCLOS mentioned above, although these results are promising they are not yet ready to be translated into in-vehicle alertness monitoring devices (although companies such as Applied Science Laboratories and LC Technologies, Inc. are making progress in this area). Despite this, increases in pupil constriction latency and saccadic velocity can be measured using the FIT machine (discussed above to measure readiness-to-perform and fitness-for-duty).

2.4.3 Other physiological/biobehavioural measures

There are numerous other devices that are capable of measuring the physiological /biobehavioural state of a driver. Examples of these measures are: tone of facial muscles, body postures and head nodding. Again, most of the devices require electrode attachment and/or other equipment intrusive to the vehicle operator. Although devices that monitor driver head nodding are generally less intrusive than others, their general problem is that operator performance has probably already declined to unsafe levels before the head nods forward in a fatigued / sleepy state.

Stimulus-response (SR) reaction tasks, to ensure attentiveness, consist of the presentation of an audio or visual signal that must be responded to by the driver within a set time. A general potential problem with such devices is that special care must be taken to ensure that the demands of the task do not interfere with, or increase, the driver's workload (eg require a response from the driver in high traffic density). Most secondary SR tasks consist initially of the presentation of a light that is mounted in a suitable location on the vehicle's control panel. The signal is presented to the driver at random intervals. Response to the light stimuli is made by use of touch pads/ keys on the steering wheel or dashboard, or through the use of a foot switch. Failure on the part of the driver to respond will instigate an audio signal to alert him or her of the missed visual stimulus. The final system response if no signal is responded to could be to turn off the vehicle's power (Mabbott et al, 1999). As Haworth et al (2000) has found there is the potential for operators to respond automatically to such devices when they are already in light sleep, so considerable care needs to be taken in system design to guard against this possibility.

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Table 4 summarises reported findings from in-vehicle, on-line, operator status monitoring devices (adapted from Haworth & Vulcan, 1991; Charlton & Ashton, 1998; Mabbott *et al.*, 1999).

Table 4: Physiological/biobehavioural monitoring devices

Test name	Measure/s	Comments
Onguard	Eye closure - buzzer warning given when eyes close.	Generally detects the onset of fatigue. Is obtrusive (driver must wear special eyeglass frames).
Dozer's alarm	Head nodding – buzzer warning given when head nods past predetermined angle.	Generally detects the onset of fatigue. But late alarm activation – i.e. after subject falls into sleepy state
MIcro-**N**od **D**etection **S**ystem (MINDS ™ Drowsiness Detection System). Advanced Safety Concepts Inc.	Head nodding- when drowsiness detected by a capacitance based sensing system embedded in the headliner above the driver, the driver is alerted by seat vibration/ lights/ drowsiness gauge.	Still in prototype stage, but perhaps similar comments to Dozer's alarm regarding late activation. Is currently being developed to be integrated with Smart Airbags.

Test name	Measure/s	Comments
Vehicle Driver's Anti-Dozing Aid (VDADA), BRTRC Technology Research Corporation, of Fairfax, Virginia, USA.	Three different headband mounted devices have been developed and laboratory tested. The device(s) contain an electronics package that establishes actuation parameters from various sensor inputs: 1) temple area are vibrator with beeper, actuated by a specially designed mercury tilt switch, sensitive to timed multi-position head nods; 2) same as 1) above, but with the addition of another sensor, an infrared sensor, aimed and timed to eyelid closings, [eye closings from one to two seconds will trigger the device], and 3) same as 1) above, with a commercial carbon dioxide, CO2, cartridge providing pulsed random blast, or bursts to temple areas. Thus it has three alerting devices: the vibrator, the beeper, and the carbon dioxide blast.	Prototype developmental testing by BRTRC on a U.S. Army contract (Rogowski et al., 1997) successfully demonstrated a proof of principle. The device monitors a driver's state of awareness and provides a mechanism to alert him or her upon detecting drowsiness. Model 1 above (tilt switch for monitoring device, vibrator, and beeper for alerting devices) has the best promising features for refinement and subsequent developmental testing. Although Model 2 (with the IR sensor) is not currently a practical device, the IR optical sensor is more accurate in detecting early signs of drowsiness than the mercury tilt switch.
Stay Alert, Good One, Inc. in Los Angeles, California.	Stay Alert device consists of a flexible band loosely secured about the user's neck while driving and has an integral bulb shaped acutator which is positioned below the user's chin. The actuator produces a tactile and an aural (a squeek sound like a toy rubber duck) warning when as the tired and drooping head allows the chin to contract the acutator. The bulb shaped acutator includes an upper rounded dome made of soft plastic and a lower elongated body secured within the flexible band. When the drooping chin of the user "falls" upon the acutator, the deformation of the soft plastic dome results in the closing of an electrical switch (powered by two watch batteries) and the warning sound or vibration is generated.	It is obtrusive and funny looking, and is not taken seriously by many. But it is undoubtedly cheaper (~$20+ US each) than any other head nodders and probably works as well. To our knowledge no test data exist.

Test name	Measure/s	Comments
Roadguard	Response to presented stimuli - buzzer warning given when no response.	Detected most fatigue events, needs shorter reaction time criteria. Might increase drivers' cognitive workload. Is highly obtrusive
Alertomatic	Response to presented stimuli – horn warning given when not responded to, then ignition turned on/off.	Not scientifically validated for 'on the road' use. Might increase drivers' cognitive workload. Is highly obtrusive.
Travelmate	Head nodding – alarm sounds when head drops.	Late alarm activation – i.e. after subject falls into sleepy state.
NOV Alert Atlas Researches Ltd, Israel.	The NOV Alert is an intelligent, wrist worn, sensor/monitor for early warning of "reduced fitness to perform" based on physiological and behavioural signals. The personal wrist unit contains the dry sensors (EMG electrodes), electronic circuitry, microprocessor and wireless transmitter. It is embedded within a wrist watch and operates automatically once it is activated.	The system is presently undergoing prototype trials with U.S. railroad industries in the northeast part of the country. We do not believe they have any confirming data or validation results. It is intended for continuous evaluation of drivers' and pilots' performance without interfering with their task and attention. It is placed over the wrist and senses the physiological signals which correlate with the level of drowsiness. Comparing to a baseline measurement, the NOV Alert can detect the trend of sleepiness and alert the driver using a built in vibrator hence arousing the driver, who must respond with appropriate wrist movements, and thus preventing (delaying) performance impairment. Unit costs will be about $100 when large quantities are purchased

Such operator status monitoring devices are generally relatively cheap, for example around a few hundred US dollars for the MINDS^{TM} system (Kithil, 2000) and most are commercially available although concurrent validity data are scarce. It seems that these devices can (to some degree) monitor the onset of fatigue. However, as Haworth et al (1991) state, such monitors do not allow the subject to drive longer without falling asleep, nor does the use of these monitors result in less deterioration in driving performance. Also, most are quite obtrusive (usually requiring some attachment to the head/face) and can produce a high number of false alarms (Charlton & Ashton, 1998). A final problem is that simple SR devices can be responded to automatically by the driver when in a light stage of sleep. The present authors are unaware of any validation of these devices against real world crash data. Thus the need to develop validated and unobtrusive detectors of driver fatigue still remains.

2.4.4 Summary

As with the previous section (describing vehicle based performance technologies), at present, systems that purport to measure fatigue through operator status fall into one of two general categories:

simple systems that are currently commercially available, but with uncertain effectiveness in terms of reliability, sensitivity and validity.

More complex systems (such as PERCLOS) that are undergoing rigorous evaluation and design, and seem potentially very effective, but are however not yet validated against real world data and are not commercially available.

Again, at the current time the authors cannot recommend any of the systems for immediate use in transportation in Australia and New Zealand in 2000. Similarly, until more complex systems are further developed and validated, it is difficult to speculate upon the position of these technologies with regard to enforcement and regulatory frameworks.

2.5 The role of the technologies in transportation in 2000 and in the future

Many devices and technologies are currently being developed which show considerable promise, amongst those are: PERCLOS, SAVE and the mathematical model 'Interdyne'. As yet such technologies are either not yet commercially available (PERCLOS, SAVE) or require more development and evaluation especially with regard to inter-individual variation in susceptibility to fatigue, the effect of different job demands on fatigue and concurrent or predictive validation against real world safety data (eg the 'Interdyne' mathematical model). Several authors including Dinges and Mallis (1998) have raised concerns about the application of the technologies and some of these concerns are discussed below.

2.5.1 The problem of validation

Validation is the most significant problem facing all of these technologies, and there is no convincing evidence that we have reached a point where we can conclude that any system has the necessary validity and reliability to detect or predict fatigue. The hardware technologies aim principally to detect fatigue here and now – a current state of drowsiness or lack of alertness - (although fitness-for-duty testing would like to predict future fatigue as well). Thus they have to demonstrate high concurrent validity. But what should the criterion variable be that is predicted by the technology? The answer may depend on whom you ask. The public might say 'crashes', the driver might say 'fatigue', the scientist might say 'sleepiness or lapses in vigilance'. The relationship between these potential criterion variables of success is complex. Are lapses in vigilance the one and only measure or even the best measure of fatigue, and do they predict crashes? They should do that, but they may only be a partial or incomplete predictor. Certainly the road environment, traffic and weather conditions will make a great contribution to whether a vigilance lapse results in a crash or not, and there may be other factors involved. In the present state of knowledge we do not know the concurrent validity of vigilance lapses or any other hardware technology measure discussed here and their ability to predict crashes, close calls or near crashes. Neither do we know much about the predictive validity of the software models for crashes. But the validity of each technology alone could be rather weak. This suggests that it might be more profitable to look at combined inputs from several sources of information about the state of the transportation system, much as SAVE does, in order to make a more powerful decision. "***If*** PERCLOS occurs ***and*** lateral lane deviations occur ***and*** the driver's previous work history or wrist activity monitor was unfavourable ***then*** there is a risk of a crash. This approach complicates the problem of validation but offers the possibility of better decisions about fatigue.

An interesting approach that may have great potential in the future is the synergy of different fatigue detection technologies where for example the efficacy of a wrist activity monitor (to inform the drivers how much sleep they have had and when they need more sleep) is combined with a PERCLOS system, lateral lane deviation assessment and driver training regarding the causes and consequences of fatigue. The U.S. Federal Motor Carrier Safety Administration (FMCSA) in conjunction with the American Trucking Associations Foundation (ATAF) are planning a large, 2-year on-the-road field study of several Fatigue Management Technologies (FMT), in trials in both Canada and the USA. Essentially, long haul truck drivers will first be afforded an individualized instruction in personal sleep management and fatigue countermeasures to assist them in managing their driving alertness. The drivers will be equipped with a Sleep Watch system which they will wear 24-hrs per day for 4-weeks. In the cab of their trucks, they will have a PERCLOS eyelid droop measurement and warning system mounted on the truck dash board, and a SafeTRACK lane tracker camera system mounted in the truck's windshield and its feedback display also positioned on the truck dash board. A black box electronic recording system will record all measures of driver and truck performance, and that of the test alertness monitor systems throughout the planned 18 months of data collection. The Howard Power Center Steering system (HPCS) made and sold by River City Products in San Antonio, Texas, USA. provides a sort of truck stability augmentation system by tapping into the castered front wheels of the truck at the axle and the tie rods of the truck, and provides a hydraulic booster to help maintain the rear wheels where the front wheels are pointed, or directed. That way, the HPCS gives the driver an augmentation system to lessen his/her workload in "fighting" the steering wheel when driving on slanted roads, curves, or especially in cross winds that tend to sway the trailer. It is the synergy of these four fatigue management technologies that will be studied to determine if they contribute to better management of the truck driver's sleep, and alertness and therefore safety while driving.

2.5.2 Integrating fatigue technology into the transport system

In the Introduction it was stated that the use to which each technology was put was a fundamental question and would be a crucial determinant of its success. They could be used as a **safety device,** such as a real time system providing the driver with instant feedback warning of imminent danger of falling asleep at the wheel. Alternatively, they could be used as a **management system** e.g. a corporate and individual driver's system which proactively manages driver work schedules, and promotes management of the amounts of rest and sleep drivers obtain, and therefore ensures the likelihood of driver alertness. 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. In the following sections we examine the pros and cons of the uses of the technologies.

First let us examine the potential use of the hardware technologies. Real world over the road studies are now sorely needed to evaluate the impact of these technologies on the transport system comprising company, driver and vehicle. There are numerous questions that need to be answered such as: what use the driver makes of the information about fatigue; what use the company makes of the information; how company and driver integrate their information.

From studies of computer assistance provided to operators of complex systems we know that depending on how accurate the assistance is, operators can come to rely heavily on the assistance or ignore it completely. That is they find it hard to integrate their own assessment with that of the technological assessment and instead rely on either their own judgement or the output of the technology. The lesson for fatigue technologies is that detection is going to have to be considerably more accurate than drivers' own self reports if it is going to be used successfully by drivers to improve safety. This problem has serious implications for the integration of hardware fatigue technology into the industry. If drivers do learn to rely heavily on the technology because they believe it is accurate, then a technological failure could be catastrophic for the driver with considerable implications for product liability for the manufacturer. If the driver believes that the hardware fatigue technology is misleading them it will be ignored totally, even if it accurately detects unsafe fatigue on some occasions; a situation which might also result in a catastrophe for the driver. There are also lessons to be learned from the introduction of intelligence into the aircraft cockpit, and they are that the relationship between the pilot and the automation or intelligence is ambivalent and complex. Pilots can rely too heavily on support systems; fight the support system or just fail to understand what the support system is doing.

Conversely, companies who 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 or alertness. A hardware technology that missed instances of driver fatigue (a risky criterion) could lead to companies setting unrealistic schedules which increased driver fatigue with consequent risk to public safety. A technology that was over-zealous in detecting fatigue might have implications for productivity.

Finally, how will the fatigue detection information be integrated with driver feedback and company information on shiftwork rosters, hazardous incidents, near misses and other safety information. What weighting and credence will be given to fatigue information in comparison to risk assessment information?

Turning to the software technologies, how might they be used or misused? The software technologies have the potential to improve scheduling by weighting it for the dangerous points on the circadian cycle and by taking in to account the driver's past work record. However, if a simple system such as Interdyne, was rigidly used it might give quite misleading predictions about how safe a driver was on a shift. This could occur because Interdyne does not incorporate true sleep length information or, because delays to the trip schedule due to loading/unloading/repair delays were not updated in the record of the driver's past work. People do not always sleep the maximum time allowed in their time off, for example if they have a sick child or any other of a hundred reasons including on-the-road insomnia. Trips do not always run to the planned schedule and time may have to be made up on the trip, with consequent loss of sleep. If the technologies were slavishly used by management to set shiftwork schedules simple software technologies might actually make drivers more unsafe overall by ignoring the other factors which affect a driver, which can be taken into account at present. The software technology could be slavishly misused to set targets for the driver or industry by using only simplistic information about the many factors impinging on a driver which cause fatigue.

2.5.3 Acceptability of the technologies

With or without convincing validation data the technologies will have considerable appeal to transport companies, but have less appeal to drivers. For example Penn and Schoen (1995) found that for every 3 drivers who were strongly in favour of on-board safety monitoring including alertness monitoring, four were completely opposed to it. Hardware technologies will 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. If a validated hardware 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 the resulting legal question is no longer one of whether the company failed to provide a safe system of work. The legal question is now one of whether the fatigue detector manufacturer is liable for providing a defective product. Of course if the hardware 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.

The other side of the same coin is that the technology has the ability to convey to operators (with somewhat less than 100% accuracy) that the driver is fatigued (if real-time information is available) or was fatigued on his last trip. In these circumstances it is arguable that the operator has a responsibility under both duty of care and road transport law chain of responsibility to address the issue, at least for the future. The information that the driver was fatigued (as measured by the device) imposes on the operator a duty to establish a system of work where this does not happen in the future, by setting better schedules.

First reports from the US Fatigue Management Technology demonstration test are that the first few drivers in field trials said that when they knew sophisticated recording devices were monitoring and recording their driving performance, they tended to be on their best driving behaviour, and they subsequently thought they drove better because they were being monitored and recorded. Additionally, one driver was convinced one of the test devices saved him from an impending highway crash. These drivers discussed the expectation that if the technologies could demonstrate they can save them crashes, even occasionally, then the drivers were more likely to accept and adopt them, and furthermore would recommend them to other drivers as well. These psychological factors will also play a part in this picture. Will the drivers initially perform better when they are being monitored, and then become complacent after becoming accustomed to the recorders? Will drivers who learn to believe in the alertness and fatigue monitoring systems "sell the idea of adopting the technologies" to other drivers?

Drivers will feel more ambivalent towards the technologies. Having a hardware technology in the cab which has the potential to provide management with feedback of drivers’ driving performance and possibly other behaviours is not likely to appeal to their workforce. This is because the technology invades drivers’ privacy to a degree and introduces an element of supervision in an industry which has traditionally attracted people who like to work without close supervision. It is the view of the present authors that should the technologies cut crash rates then drivers will be more tolerant of the invasion of their privacy.

Software technology will also have appeal to company management because it has the potential to provide a means of setting schedules which have been ‘certified’ as safe by the software provider. Like the hardware technologies, the software technologies have the potential to absolve the company management of further responsibility to provide safe trip schedules. If there is a crash due to fatigue then the company could be seen to have adopted safe work practices by using the fatigue software to set the schedule. The legal question then is whether the software provider is liable for providing a defective product. If the software does cut crash rates there is the added attraction to install it of fewer legal cases and less vehicle down time.

Drivers will also come to realise that both the hardware and software technologies will shift the onus for managing fatigue away from the company and entirely on to them. Companies have played their part in the mutual responsibility to provide a safe system of work by installing the technology, and it only remains for drivers to play their part by obeying it. Furthermore there might be the added suspicion that drivers might be replaced if they cannot work to meet the target schedule set by the software technology or drive until the hardware technology tells them they must stop. They might also suspect that the technologies will reduce their discretion to negotiate their work, such as negotiating trip schedules or for a relief driver, with management. They might also have concerns that the software technology does not take individual differences in susceptibility to fatigue, such as age, into account or differences in workload.

For these reasons the present authors believe that the fatigue detection and prediction technologies should operate for the present within a legislative hours of service regime, such as exists in Australia. This will provide some protection against the technologies being used as the sole company fatigue management system. It is the view of the present authors that the potential of the technologies to absolve companies of their responsibility to appropriately manage driver fatigue could create a dangerous situation. It could put companies beyond the reach of both statutory, criminal and occupational safety and health legislation, and would certainly reduce their liability under such legislation. Conversely the technologies might place greater responsibility on the person who has least discretion in the transport task, the driver.

To return to the framing question that was asked in the introduction "how will the technologies be used-safety device or management system?" From the foregoing, it is the view of the present authors that the hardware technologies should **never** be used as **the** company fatigue management system. There will be a strong temptation for companies to use them as management systems. Hardware technologies should only be seen as having the potential to be a last ditch safety device. However, the output of hardware technologies could usefully feed into company fatigue management systems to provide real time risk assessment. However, hardware technology output should **never** be the only input into a management system. Other inputs should at least come from validated software technologies, mutual assessment of fitness for duty and other risk assessments.

2.6 The place of the technologies vis a vis other enforcement and regulatory frameworks

2.6.1 Hours of work and fatigue technology

It is useful to ask the question "why do we need fatigue detection technologies when we already have regulations (hours of service regulations or HOS) to control fatigue"? One answer must be that those regulations do not always do what they are supposed to do and control fatigue, as evidenced by the number of fatigue related crashes. It is useful to ask a second question "why do the hours of service regulations not control fatigue and would fatigue detection technologies control fatigue any better than HOS"? Taking the first question, there are two main reasons why HOS do not control fatigue.

Hours of work are not the principal cause of fatigue. It is the timing and duration of rest and sleep, or lack thereof, and circadian physiology which principally determine fatigue. So HOS control fatigue in only an indirect fashion. It is of interest to note in support of this that the Interdyne Fatigue Audit software technology (see Section 2), which uses the timing and duration of hours of work as its data source, has only weak correlations between the predicted fatigue score and real world measures of fatigue, and that this model only accounts for 5% of the variance in real world fatigue measures.

The HOS are notoriously difficult to enforce. The USA, Australia and New Zealand use paper based log books which are completed by the driver. These are apparently subject to considerable abuse and keeping two log books reflecting "legal working hours" and "compensable working hours" is not uncommon. The log books must be produced on demand by a police officer. Comprehensive policing of the log books of the transport fleet would be an enormous and costly task, so it is not surprising that enforcement is sketchy. The European Union uses in-vehicle tachographs to monitor hours of work and these suffer similar problems to log books; the tachograph can be corrupted and comprehensive enforcement is not feasible. In an industry in which drivers are paid by the hour or kilometre travelled, and close supervision is impossible, there is a strong incentive to drive as far as possible in a day and ignore the regulations. Fatigue technologies have the potential to improve fatigue management by complementing the legislative hours of service regime.

2.6.2 Fatigue technology & hours of work

Let us turn to the second question: "would fatigue detection technologies control fatigue any better than HOS"? Consider a scenario where the hardware technologies were a requirement in the road transport industry. Say, vehicles were required to be fitted with a PERCLOS system. If PERCLOS sounded an alarm what could happen, and would the driver stop? What do we know about compliance with warnings and advisories that might provide an answer? When seat belts were first introduced into vehicles only about 20% of passengers used them. They had to be rigorously enforced to achieve compliance. How feasible is that with fatigue technology? In the area of compliance with warning signs Hartley (Curley v. Fremantle Port Authority and City of Rockingham, District Court Action no. 7267 of 1989) reviewed compliance with product warning labels. "*To summarise, the average taken from the data we have suggests that 28% of people comply with a visible warning sign. This figure will be moderated by the factors noted above, particularly sign comprehension, the perceived risk of the situation, what others are doing and the cost of compliance.*" These considerations suggest that voluntary compliance with warnings and advisories is around 20% even in situations where there is little cost to compliance as there was in the studies reviewed by Hartley. In an industry where close supervision is impossible, where time is money and compliance could be costly, voluntary compliance is likely to be even less frequent.

Let us take a second scenario where PERCLOS was installed in a vehicle, and sounded an alarm and provided "*countermeasures*" as has been proposed. What would those countermeasures entail? Possible countermeasures could include spraying peppermint, cooling the cab, providing auditory stimulation, or stopping the vehicle. Do these countermeasures work? Horne and Reyner (2000) state: "*Drivers falling asleep at the wheel should stop driving as soon as possible. Motoring organisations advocate various in-vehicle methods to counteract sleepiness, such as cold air to the face (opening the window) or turning up the car radio/tape player, but there is no sound evidence on which to base this. In fact we (Reyner and Horne, 1998b) have shown that both methods provide only temporary benefit, being only partially effective for a short period of time (about 15 min). That is, these techniques should not be used to prolong driving, but may provide enough time for the driver to locate and stop at a suitable place to park and rest. In some cases, listening to the radio distracts sleepy drivers from being so aware of their sleepiness and impaired driving..... As sleep is the cure for sleepiness, it is far better to take a short (10-15 min) nap if possible (Horne and Reyner, 1996; Reyner and Horne, 1997).*" So at the best, PERCLOS countermeasures might just keep a driver alert enough to get off the road safely, or might stop the vehicle. Could the driver sleep as Horne and Reyner advocate? That would depend on location and conditions. If it occurred in the metropolitan area, on a free way or in high temperatures the answer is probably no, not least because others might ask the driver to move on. If it occurred in the country sleep might be more feasible if the driver could find an appropriate off road rest area.

In conclusion, hardware technologies such as PERCLOS are unlikely to play a major role in fatigue management at present because useful countermeasures are limited to sleep or stimulant drugs such as caffeine. The technologies will confirm what the drivers already know, that they need sleep. Their use will be limited to a last ditch safety device.

2.6.3 Fatigue prediction technologies and fatigue management

Given the minor role that hardware technologies such as PERCLOS are likely to play in fatigue management in the future, what is the role of the software technologies such as the Interdyne Fatigue Audit, The Three- Process Model of Alertness (by Åkerstedt et al.) and the US Army's Sleep Management System and how do they relate to existing enforcement and regulatory frameworks? Bearing in mind the need to establish the predictive validity of the models, they have the potential to compensate for the weakness of the existing regulatory framework: that hours of work are an indirect cause of fatigue and therefore are not good predictors of fatigue. The models focus on the principal causes of fatigue: the circadian biological rhythm of alertness and the need for a minimum amount of sleep. The US Army model goes furthest in measuring the amount of sleep obtained by using a wrist activity monitor, and then telling operators that they need more sleep if too little has been obtained, or to plan time off for a long period of sleep. The models therefore have the potential to provide information which can be used in planning schedules and rosters which prevent the occurrence of dangerous levels of sleepiness. There is the possibility that the models can be extended to include information about other sources of fatigue including job demands and individual differences.

The way they might be used within the existing regulatory framework is that information provided by the models might be projected into schedules which have been set according to existing regulations. Thus a transport delivery schedule might be set and a driver, whose projected fatigue profile provided by the model fitted the trip schedule, would be selected to accomplish the task. Alternatively some schedules could be re-designed to provide sufficient time off for adequate sleep during the trip. This approach could be adopted company wide so that the company work load of its work force could be tailored to meet the freight task safely. Given the company fatigue profile of its work force, new contracts could be accepted or rejected, and new drivers hired or not to meet the task.

This approach overcomes the ever present problem in road transport that drivers may be given legitimate tasks but little attention is paid to their past work load, which must be a main source of the variance in their fatigue. It is hard for schedulers to take account of the work load involved in schedules they have set in the past and even harder for them to take account of drivers' extra work when there are delays due to delivery/loading and breakdowns. The models, especially in combination with a wrist activity monitor, are well placed to incorporate past work load and sleep into future planning. The models therefore have the potential to provide safe flexibility within transport operations whilst operating within a regulatory framework. The potential for the hardware technologies to be misused as fatigue management systems also suggests they need to be used within a regulatory framework of hours of service.

2.6.4 Fatigue technologies & enforcement

Enforcement is a problematic issue for any fatigue detection technology. This has been alluded to several times and it is especially problematic because the present enforcement system focuses on the person with the least discretion in the transport operation: the driver. Within a framework of using the hardware and software technology discussed above there is the potential to provide better enforcement at the point of source of fatigue: the person setting the schedules and rosters. This enforcement strategy would require that the enforcement agency had the authority to enter premises to audit the schedules and rosters and confirm that they operated within the regulatory framework and that the information provided by the software technology had been used to manage company workforce and individual workload. At present the Police Services do not have the authority to enter premises without reasonable suspicion that an offence has been committed. The agencies in several states that do have the authority to enter business premises to audit systems of work are the Occupational Safety and Health Commissions. Thus these Commissions are best placed to enforce both existing regulations and future developments with these software technologies.

3. CONCLUSIONS

Despite promising developments such technologies should not be a substitute for setting standards for the functional capabilities of the transport operator (Dinges, 1997). Thus the use of fatigue management programmes, better education of drivers and society as a whole regarding the danger of fatigue, greater use of engineering countermeasures (for example the design of roadways) and more research into the nature and consequences of fatigue amongst drivers are critical.

Satisfactory data on the real world concurrent and predictive validity of the fatigue technologies are not yet available, and may not be for some time. Many of the technologies are first generation, and there may be benefits to combining technologies to provide a more powerful assessment of fatigue. The combination of hardware and software technologies are obvious candidates for integration, but so are some hardware technologies as demonstrated in SAVE.

Given the concerns about the validity and use of the fatigue technologies it is inappropriate to mandate their use at this time. However, they may have a judicious role when validated. First, the hardware technologies such as PERCLOS could have a role as a last ditch safety device. However the hardware technologies such as PERCLOS should **not** be used as **the** company fatigue management system. Second, the output of hardware technologies could feed in to a company fatigue management system, if their output can be integrated into the company risk assessment including shiftwork scheduling. For example the hardware fatigue technologies may assist in confirming what the software technologies suggest, that particular shift combinations appear to be unsafe.

For their part, the software technologies are certainly not validated sufficiently well to be used as company fatigue management systems. Indeed they may only ever be useful to provide information to feed into a company fatigue management system. The other information required in the system could at least include a mutual assessment of present fitness to work, trip schedule risk assessments based upon monitoring the hardware technology outputs and company wide workload.

What these conclusions suggest is that large scale, industry wide, data bases incorporating information from the fatigue technologies, shiftwork rosters and risk assessments will be critical to the further development and ultimate validation of the technologies.

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