Fatigue and distraction detection

A review of commercially available devices to detect fatigue and distraction in drivers

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SWOV

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Prevent crashes
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Abstract

Fatigue and distraction are important risk factors for road crashes, particularly in professions that involve driving long hours (such as drivers of trucks, buses and taxis). To mitigate the risks, systems have been developed to detect driver fatigue and distraction. The recent interest has led to an explosion of the number of devices currently on the market, or start-ups that aim for funding to develop their products and bring these to market. This study presents a review of the potential effectiveness of these systems.

Previous reviews of such systems have either (1) focused on the scientific evidence underlying such systems, (2) provided an overview and classification without comparing systems, or (3) compared a relatively small number of systems. In response to a call from Shell Global Solutions International B.V., BP International Limited, Total S.A., and Chevron Services Company, this study extends this work by (1) considering a substantially larger number of devices, (2) comparing these devices on a broad range of safety and acceptability-related criteria, with the overall aim to (3) recommend a list of devices to further explore and compare in a field test.

Due to extensive scientific evaluation, low cost, and high acceptability, fitness-for-duty tests (PVT, FIT and/or OSPAT) score best on the original set of criteria and could be recommended. These systems, however, do not monitor fatigue in real time. Therefore, fitness-for-duty tests should be compared to real-time systems, with the most promising candidates being dry EEG (Smart Cap and/or B-alert) and computer vision systems (Guardian, EyeSight, Stonkam, Mobileye, Streamax and Nauto). It is, however, not clear how acceptable these devices would be to drivers. Therefore, a broad field study is recommended, which may also include systems that combine activity tracking and computational modelling (Readiband and/or Cat smartband), Optalert (an established method using eyelid closure) and steering movements (Bosch). If the aim is to monitor fatigue *and* distraction in real-time, only computer visions that focus on the driver are plausible candidates (Guardian, Eyesight, Stonkam, Streamax and Nauto, from the above list), but drivers may find these devices difficult to accept. Overall, there appears to be no single perfect fatigue and distraction system that meets all requirements, and thus a combination of devices and methods may be needed.

Summary

A substantial portion of work-related deaths are due to road crashes during the course of work or on the way to and from work, and fatigue and distraction are known risk factors for such road crashes. While fatigue management programmes (e.g., maximum driving and minimum resting hours) are at the core of preventing fatigue related crashes, not all crashes may be prevented with such traditional measures. To reduce the risks of fatigue and distraction, devices have therefore been developed to warn drivers before starting their journey or while driving. The present report, commissioned by Shell Global Solutions International B.V., BP International Limited, Total S.A., and Chevron Services Company, provides a detailed comparison of around 100 such technologies and systems, with the overall aim to provide a recommendation on which devices to consider for further testing or use.

The first step in the comparison was the compilation of the list of devices. Devices were added that (1) were brought forward by the commissioners of this review, (2) were described in past reviews (mostly related to fatigue detection), (3) were found in an internet search for devices that specifically target distraction, or (4) were suggested by colleagues or suppliers. In a second step, devices were screened to determine (i) whether sufficient information was available to rate the device, (ii) whether the device was still on the market, and (iii) whether the device exclusively served to detect fatigue and / or distraction (or the consequences of fatigue and distraction) instead of a different general purpose (e.g., eye tracking) or a different purpose (e.g., illegal substance use).

In a third and important step, devices were rated on eight criteria: validity, intrusiveness, availability, robustness, sustainability, acceptability, cost, and compatibility with other devices in the vehicle or used by the driver. It was also determined whether the device would be portable, detect fatigue and distraction or fatigue as a 'stand-alone' device, in a non-intrusive way, or whether it would involve wearing a sensor, whether it would provide real-time feedback, and what kind of feedback it would provide. To make these judgments various sources were used: (a) the website of the supplier, (b) the scientific literature (Google scholar search, past reviews), (c) online articles (e.g., blogs, online newspapers, news websites), (d) online videos (from suppliers and users), (e) reviews from users on commercial websites and forums, and (f) direct contact with suppliers.

While past reviews tended to classify devices into those that test fatigue before driving (fitness-for-duty tests), systems that monitor the driver, and systems that monitor driving performance, a more fine-grained distinction proved more appropriate in the present context. The present review therefore distinguishes devices that use (1) heart rate measurements, (2) head nodding, (3) EEG recordings, (4) measurements to test fitness-for-duty, (5) computer vision monitoring the road, (6) computer vision monitoring the driver, (7) computer vision monitoring both the road and the driver, (8) the closure of the eyelids (PERCLOS), (9) eye movements, (10) steering movements, (11) computational models to predict fatigue, (12) measurement of body temperature, (13) skin conductance, (14) video recordings and human analysis, (15) activity tracking in combination with a fatigue model. Based on the criteria, a subset of these systems was selected.

Judged strictly on the eight criteria outlined above, fitness-for-duty tests achieved the best scores, specifically for validity, cost, and acceptability. These tests, however, do not provide real-time feedback and only focus on fatigue. The only systems that detect distraction directly are the computer vision systems and eye trackers, which both use one or more cameras to monitor the driver's face (which may lead to privacy concerns and, hence, acceptability issues). Computer vision systems have the advantage (over eye trackers) that they can also monitor for phone use, smoking, emotion (e.g., road rage), eating and drinking, which may also affect driving. Indirect measurements of distraction may be obtained from computer vision systems that monitor the road, and systems that monitor steering movements, but whether these systems can provide feedback with sufficient time left to prevent a crash, is unclear. Computer vision systems, however, suffer from a lack of scientific evidence of their validity and robustness, and suppliers are often hesitant to share their own test results, because of fierce competition in the market.

If the dominant goal is to detect fatigue, dry EEG systems that can be embedded inside a cap may provide a suitable alternative, as they have been tested in the scientific literature and show good validity, and there are suggestions that these systems may be sufficiently comfortable. Systems that monitor for eyelid closure have also been tested extensively in the literature and show good validity, but may be outperformed by computer vision and eye tracking systems that can also measure distraction. If computer vision systems, EEG systems and eyelid closure systems are found to cause too many acceptability issues, more elaborate fatigue predictions than from fitness-for-duty tests may be obtained from activity and sleep trackers that are combined with a fatigue model. A system that monitors steering movements in addition to a range of other variables, could provide a further alternative if the additional variables can be shown to compensate for poor validity of steering movements alone in real-world conditions.

Together, the results suggest that there is not a single system that outperforms all other systems on all criteria. For optimal monitoring for fatigue and distraction, a combination of systems or system features may therefore be needed. Selection of a particular system will also depend on user preferences. Before selecting a specific device, it is recommended to compare a range of devices in real-world conditions. Depending on the number of devices one would want to compare, the findings suggest that systems to consider are: (1) B-alert or Smart Cap (EEG), (2) Mobileye (monitoring the road), (3) Guardian, Eyesight and Stonkam (monitoring the driver, either higher-cost, or lower-cost), and (4) Nauto and Streamax (monitoring the road and the driver), PVT, OSPAT and/or FIT (fitness-for-duty). On the reserve list would be Readiband or Cat Smartband (activity trackers), Optalert (PERCLOS) and Bosch (steering movements).

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Preface

This report presents an overview of devices to detect fatigue and distraction in drivers. Both factors strongly increase the risk of road traffic crashes, particularly in workers who need to drive long distances as part of their job. One such domain is the oil and gas industry, where personnel need to transport highly flammable substances in large vehicles across long distances, not only increasing the risk of a road crash, but also increasing the potential damage such a road crash could cause.

It is for this reason that Shell Global Solutions International B.V., BP International Limited, Total S.A., and Chevron Services Company have asked SWOV to conduct an independent review of the literature on existing, commercially available devices, or promising devices that can be expected to be soon brought to market, that may help prevent road crashes due to fatigue and distraction.

A broad search strategy was employed to avoid excluding potentially useful systems at an early stage. The result is this overview of more than 100 systems, products and devices. Information was extracted from the scientific literature, websites of companies, phone and online video conversations with representatives, interactions with colleagues, YouTube videos, newspaper articles and web texts. Using a set of predefined criteria, devices were evaluated on the basis of the information that was available. These evaluations were then used to compile a list of devices that could form a starting point for a field study that should demonstrate whether the systems will function in an actual work environment, whether drivers will accept the systems, and how sustainable and cost-effective the various solutions are.

Acknowledgments

1 Introduction

Road crashes are an important cause of workplace deaths, which may (EU countries) or may not (Canada and the US) include crashes during commuting (Charbotel et al., 2010). Based on coroner's records in Australia between 1982 and 1984 (Harrison, Mandryk & Frommer, 1993), for example, it was estimated that around 39% of workplace deaths were due to road crashes (24% in the course of work and 15% while commuting) and that these deaths disproportionately involved older drivers. A similar number (40%) of work-related deaths due to road crashes was found by the European Transport Safety Council (ETSC; SWOV, 2017). Likewise, on the basis of police records in France in 1997, Charbotel et al. (2001) found that around 9.9% of victims of road crashes were injured during work hours and 18.6% while commuting, and road crashes caused respectively 40% and 20% of the workplace deaths. A comparison between New-Zealand (16%), the USA (22%) and Australia (31%) showed that work-related road deaths were particularly prevalent in Australia, especially in older male truck drivers (Driscoll et al., 2005).These statistics were found to be relatively stable over time (Charbotel et al., 2010).

It has been suggested that fatigue and distraction play an important role in these work-related road crashes. One estimate indicated that around 7.6% of the work-related crashes of male drivers involved fatigue (Boufous & Williamson, 2006), lagging only behind speeding as a cause of such crashes (around 15% in male drivers). Compared to other causes, work-related crashes due to fatigue were more likely to result in fatalities, with possible reasons that such crashes more often occurred with trucks, and more often involved alcohol consumption and speeding (Williamson & Boufous, 2007). Fatigue work-related crashes most often occurred at dawn, in contrast to crashes unrelated to work, which mostly occurred during rush hour (Williamson & Boufous, 2007).

Distraction is a further important risk factor. For example, Dingus et al. (2016) estimated that around 68% of drivers (related and unrelated to work) were somehow distracted prior to a road crash (Klauer et al. (2014) estimated this number to be 78%), that drivers were engaged in some form of distraction around 51% of the time, that distracted driving increased the risk of a road crash two-fold, and that around 36% of crashes could be prevented if no distraction were present. Activities that increased the risk of a road crash included dialling a number on a mobile phone, reaching for a mobile phone, texting, reaching for other objects, eating and drinking, and looking at roadside objects (Klauer et al., 2014), although quick glances were considered to be safe (Dingus & Klauer, 2008; Klauer et al., 2006). The strongest effects of distraction were found for younger (<30 years) and older (>65 years) drivers, where the risk for younger drivers was driven by the high frequency of distraction and the risk of older drivers by their susceptibility to the effects of distraction (Guo et al., 2017). Even in the absence of distracting elements, mind-wandering (associated with monotonous driving) impairs driving performance (Baldwin et al., 2017).

1.1   Studying the cause of road crashes

The above numbers suggest that fatigue and distraction are important causes of work-related road crashes, but estimating their exact contribution to the total number of crashes and fatalities is less straightforward than it seems. From police records it is rarely clear whether a road crash was caused by fatigue (Li, Yamamoto & Zhang, 2018). Guo (2019) distinguishes three main methods to study the role of fatigue in road crashes, each having their advantages and limitations. These are: (1) the analysis of crash databases, (2) simulator studies, (3) naturalistic driving studies (Guo, 2019). Methods not specifically described by Guo (2019), but also often used, are in-depth studies, in which specific road crashes are investigated in detail (Larsen, 2004; Mackay et al., 1985), and questionnaires and self-reports (e.g., Meng et al., 2015; Vanlaar et al., 2008).

The challenge in the analysis of crash databases is to determine which crashes were the result of fatigue. Knipling & Wang (1994) suggest a few reasons why police records do not always list fatigue as the cause of a road crash. Forms do not always ask for it; there may be a lack of evidence for the involvement of fatigue (see also DaCoTA, 2012), and fatigue may be underreported by those involved in road crashes not willing to admit they were driving while tired. Numbers based on crash databases are therefore likely to underestimate the role of fatigue and distraction in road crashes. As a consequence, different sources may result in different conclusions, depending on how fatigue was defined, or how likely fatigue was reported as a possible cause of the crash. For example, questionnaire data filled in by truck drivers suggested that around 11% of crashes had involved fatigue (Gander et al., 2006). This percentage is in sharp contrast with the mere 5% of police reports reporting fatigue (Dingus et al., 2006).

Other methods have therefore been explored, including driving simulator studies. The advantage of simulator studies is that settings can be experimentally controlled. For example, by varying the scenery, Thiffault & Bergeron (2003) found that monotonous surroundings led to more fatigue in drivers. Monotonous driving was also found to increase distraction in the form of mind wandering (Baldwin et al., 2017). Likewise, Ting et al. (2008) found prolonged high-way driving led to higher levels of fatigue (both in terms of fatigue ratings and reaction times), and as a consequence, it was recommended that uninterrupted driving time should be limited to around 80 minutes. Evidence of increasing levels of fatigue during prolonged driving were also found using surface electromyography (EMG, measuring muscle activity) of the shoulder region, and electroencephalography (EEG, measuring brain wave activity) showing increased alpha and theta waves and reduced beta waves suggestive of increased fatigue in monotonous driving (Jagannath & Balasubramanian, 2014).

A further advantage of driving simulator studies is that decreased driving performance due to fatigue has no real-life consequences, and thereby such studies provide a safe environment to examine the effects of fatigue on driving. Driving simulator studies often manipulate the effects of fatigue by varying the amount of sleep before driving in the simulator or the driving interval in the simulator. For example, a comparison of driving after a night-shift and driving after a normal shift, showed increased errors (wheels outside lane markings), shorter times until such errors, increased durations of eye closure, and higher levels of subjective fatigue (Åkerstedt et al., 2005). By examining the effect of the time since the start of the simulator journey, prolonged driving was shown to increase running off the road events, and to lead to more trouble to approach maximum speed as closely as possible (Kee, Tamrin & Goh, 2010). Because errors in driving simulators have no real world consequences, it has been questioned how informative such driving conditions are for real-world driving. Studies have therefore directly compared the effects in simulated and real driving. The results suggest that the effects of fatigue in the two driving conditions are similar, but not identical. For example, simulated driving was found to similarly affect the number of lane excursions, but showed stronger effects after prolonged driving (Davenne et al., 2012). Philip et al., (2005) also found similar number of lane excursions in both

conditions, but found that amplitudes of crossings may be larger in simulated driving. While simulated driving can therefore be used as a method to study the effects of fatigue on driving, results will have to be interpreted with some caution when extrapolating findings to real world driving.

A third method to study the involvement of fatigue and distraction in road crashes are natural driving studies. These studies involve placing equipment to monitor drivers during normal use of their vehicles, including cameras, GPS, and speedometers (Guo, 2019; Barnard et al., 2016; Van Nes et al., 2019; Neale et al., 2005). Crashes or surrogate crashes (near-crashes, e.g., involving fast braking) are automatically detected and the interval before such events is analysed to reveal the possible cause of the event. The advantage over simulator studies is that drivers are observed in their natural environment. A limitation that is shared with simulator studies, is that crashes are relatively infrequent events, and large amounts of data need to be collected and analysed in order to reliably analyse the possible causes of a crash (Guo, 2019). By comparing intervals before a crash to randomly selected intervals with model driving (driver being alert and paying attention) and all driving (any random interval not preceding a crash), driver errors were found to most strongly increase the risk of a crash, with an odds ratio (OR) of around 18 and a prevalence of around 5%, but important roles for drowsiness and fatigue (OR = 3.4, prevalence = 1.6%) and distraction (OR = 2, prevalence = 52%, Dingus et al., 2016) were also observed. The effect of distraction was strongest for activities that took attention away from the road. Distraction that did not draw attention away from the road only affected driving when compared to model driving (alert driving). The most common distracting activities involved interactions with a passenger and talking or listening on hands-free phones (Dingus et al., 2019).

Naturalistic driving studies that specifically focus on truck drivers, have estimated distraction to be involved in 6.5% of critical incidents (in the absence of actual crashes; Hanowski, Perez & Dingus, 2005). While significantly lower than the main cause of judgement error (77%), distraction still accounts for a large portion of crashes. These distraction events were attributable to a small number of drivers (Hanowski, Perez & Dingus, 2005), and single drivers were found to relatively often have critical events compared to team drivers. This latter conclusion was confirmed by Dingus et al. (2006), who suggested that team drivers may drive less aggressively to avoid waking up their sleeping team partners. Dingus et al. (2006) also found that fatigue related incidents of truck drivers varied by time of the day, with largest numbers in the late afternoon and early mornings. The effect of fatigue was smaller than that of busy traffic, and therefore avoiding driving during evenings to counteract effects of fatigue may not be effective, due to higher levels of traffic during alternative hours.

A related, but yet unexplored source of naturalistic driving data may be the large amounts of video footage collected by various companies that use computer vision to detect fatigue and distraction in drivers (e.g., Nauto, Eyesight, Idrive, Seeing Machines), although this would depend on whether these companies would be willing to share their data for research purposes and on possible privacy issues with such data. Such video footage is often annotated, first by automatic detection of safety critical events, and often verified by human operators. In some instances, only video footage of the seconds before and after the event are stored, but this would still provide a wealth of information about possible causes of road crashes (e.g., phone use, fatigue, eating, talking to passenger). While naturalistic driving studies often need to be supported by public funding, users of computer vision systems automatically contribute to generating new data on possible causes of road crashes, and the amount of data available from such sources is soon expected to expand beyond what publicly funded naturalistic driving studies could collect.

In-depth studies are a further method used to study the cause of road crashes. With this method, specific road crashes are investigated in detail by contacting the people involved for interviews about the circumstances surrounding the road crash, and the road setting is inspected for clues about the cause of the crash. A related method is to analyse detailed police reports for such

information, which may reduce the amount of time needed for each case and allow for more cases to be studied. On the basis of on the spot interviews of 679 sleep related accidents and police records (for comparison), Horne & Reyner (1995) estimated that around 16% of crashes on major roads and 20% of crashes on midland motorways involved fatigue, with peak frequencies of crashes at 2am, 6am and 4pm, mostly involving young men. Using a similar method, but excluding crashes under poor weather and road conditions or on junctions, Philip et al. (2001) estimated around 10% of crashes to involve fatigue, with crashes due to fatigue more likely resulting in fatalities or severe injuries. Using in-depth information of 856 crashes with serious injuries, it was found that around 58% of crashes showed evidence of driver distraction (Beanland et al., 2013). A much lower number was found in interviews in the emergency room, where around 8% of crashes were estimated to be due to distraction (Bakiri et al., 2013). Also using interviews in the emergency room, McEvoy et al. (2007) found that distraction was involved in around 14% of crashes.

In-depth studies are labour-intensive, and while providing detailed information about each case, may provide a relatively small sample of accidents. Another approach therefore is to use surveys in which people are asked about how often they think they are fatigued or distracted while driving. There are many of such studies. For example, McEvoy et al. (2006) conducted a survey among 1347 drivers, and observed that drivers indicated to be engaged in distracting activities around every six minutes. A survey of 1211 drivers found that around 60% of drivers used their phones while driving in the previous 30 days (Gliklich, Guo & Bergmark, 2016). In a survey of 4600 drivers, around 9-10% of accidents were found to involve fatigue (Maycock, 1997). Disadvantages of survey studies is that not everyone responds, and that answers of respondents may be biased by expectations about what the researcher is after and what are socially acceptable responses.

1.2   Fatigue crash prevention

The first step in preventing fatigue related crashes is an adequate fatigue management programme, with frequent breaks from driving and opportunities to take a rest during such breaks. Such programmes alone, however, will not prevent all fatigue related crashes, which is where technology to monitor for fatigue can a play a role.

To understand how effective the various systems may be, it is important to understand that there are multiple sources of fatigue, which each may have different effects on driving performance. This study draws on distinctions made in the various reviews of fatigue detection systems. For example, Dawson, Searle & Paterson (2014) suggest that fatigue is the result of a combination of factors, including (1) the duration of prior sleep, (2) the duration of wakefulness (the time since last sleep), and (3) time of the day (with expected dips in alertness early in the morning and just after lunch). Mabry, Glenn & Hickman (2019) indicate that fatigue can refer to different phenomena: (1) fatigue and (2) drowsiness. Fatigue is a state of reduced physical or mental alertness that impairs performance, often the result of mental or physical exertion, but not necessarily linked to (a lack of) sleep (Mabry et al., 2019). Drowsiness refers to an impairment of performance due to lack of sleep, boredom, or hunger. Often, fatigue is used to describe both fatigue and drowsiness (Mabry et al., 2019), and this review will follow this denotation.

It is also important to realise that fatigue related incidents are the final stage of the fatigue sequence, and that there are many opportunities to intervene before such incidents happen. Fatigue related incidents are preceded by (1) fatigue related errors, (2) symptoms of fatigue, (3) insufficient sleep, and (4) insufficient sleep opportunity (Dawson et al., 2014). Some fatigue detection systems, such as lane drift detection, intervene at the stage of fatigue related errors. For effective intervention, this may be too late and intervention at an earlier stage would be necessary (e.g., by detecting fatigue related errors, symptoms of fatigue, or insufficient sleep).

For distraction, early intervention may be more difficult to achieve. An exception may be internal distraction in the form of mind wandering or 'highway hypnosis', which may be detected using EEG measures (Baldwin et al., 2017; Compton, Gearinger & Wild, 2019; Lin et al., 2016), eye tracking (Benedek et al., 2017), and heart rate measurements (Pepin et al., 2018).

1.3 Categories of detection systems

It is beneficial to try and categorise the various systems that aim to detect fatigue and distraction in drivers, because within categories, more meaningful comparisons can be made between devices, and categorising may also help to understand the differences between systems. There is no single categorisation that works for all system overviews, because over time some types of systems may no longer be in operation, or new principles and systems may have been developed. The various existing reviews of fatigue and distraction detection systems have therefore suggested different categories, although some overlap can also be observed. Different categories may also be distinguished because some reviews focus on fatigue, whereas others examine both fatigue and distraction.

Dawson et al. (2014) focus on fatigue detection and distinguish between fitness-for-duty tests (fatigue measured before the shift starts), continuous operator monitoring (signs of driver fatigue, measured continuously while driving), and performance-based monitoring (driving performance measured continuously while driving). Hartley et al. (2000) also focus on fatigue and propose four categories: fitness-for-duty technologies, mathematical models of alertness combined with ambulatory technologies, vehicle-based performance technologies and in-vehicle, online, operator status monitoring technologies (adding mathematical models to the list of Dawson et al., 2014). Kerick et al. (2013) also focus on fatigue and distinguish between vehicle-environment monitoring, operator-vehicle monitoring, operator online monitoring, fitness-for-duty tests, and biomathematical models (and add an additional hybrid approach that combines various techniques). A recent review by the Australian National Heavy Vehicle Regulator (NHVR, 2019) focuses on fatigue and distraction and introduces six categories: fitness-for-duty tests, continuous operator monitoring (oculomotor measurements), continuous operator monitoring (EEG), other continuous operator monitoring, technologies, performance-based monitoring, vehicle related technologies (including crash avoidance technologies), very much in line with Dawson et al. (2014), but splitting the continuous operator monitoring category in three subcategories, and adding vehicle related technologies. Mabry et al. (2019) again focus on fatigue and also use six categories: physiological sensors, wearable systems, driver behaviour monitoring, computer vision systems, driver performance systems and hybrid systems, focusing, more than the other reviews, on the sensors used for detecting fatigue rather than the type of test.

Because the current review describes an even larger number of systems and aims to both examine fatigue and distraction detection, a more fine-grained distinction was used. For this distinction, the main system-specific technology was used (e.g., EEG, heart rate, computer vision). Some of the systems use multiple technologies (hybrid systems). Placing such systems in a separate category, however, was not conducive to comparison with other devices. Often different hybrid systems combine different types of technologies, hampering meaningful comparisons. The present analysis therefore placed such systems inside the category that appears to be the main focus of the system.

One major development in the field of fatigue and distraction is the use of computer vision technology. Past classifications often placed such systems in categories that reflect what is being analysed: operator monitoring for systems that analyse driver images, and performance monitoring for systems that analyse images of the road ahead. Newer systems, however,

sometimes combine both and therefore a separate computer vision category made more sense, also because it highlights the main technology used in such systems. Within the computer vision category three sub-categories can be distinguished: systems that use a camera facing the driver, systems that use a camera facing the road, and systems that use both types of cameras.

To get a better sense of past classification systems, the next sections will briefly describe the two main categories of systems that have been distinguished: operator monitoring (focusing on the driver) and performance monitoring (focusing on driving performance). A third category that is often used is that of fitness-for-duty-tests, but these will be described in a separate section.

1.3.1 Continuous operator monitoring

Almost all categorisations of systems distinguish between monitoring the operator and monitoring performance. In continuous operator monitoring, which focuses on the driver, sensors are used to deduce information about the driver's current state of fatigue and distraction. Such systems will provide a warning when estimates of the level of fatigue or distraction exceed a certain threshold, which can be set individually, or can depend on other information, for example about the number of hours slept, and the number of hours driven. Some continuous operator monitoring systems can also detect distraction, particularly those systems that use computer vision to analyse driver images, as well as eye tracking systems. Brain wave activity, measured with EEG systems may also detect internal distraction in the form of mind wandering (Baldwin et al., 2017; Compton, Gearinger & Wild, 2019; Lin et al., 2016).

While the number of operatorrelated signals that measure distraction may be limited, a large number of such signals indicate fatigue in drivers. Increasing levels of fatigue result in a decrease in heart rate, an increase in heart rate variability (Jiao et al., 2004; Li & Chung, 2013; Vicente et al., 2016), a lower blood oxygen rate, a decrease in muscle strength, an increase in tremor, an increase of alpha and theta brain waves (as measured with EEG), increased pupil dilation, longer blink duration, slower eyelid movements, head nodding and yawning. In addition, there are a number of performance related signals, including poorer steering control, increased speed variability and increased reaction times (Lupova, n.d.).

Despite having this broad range of indicators of fatigue in humans, operator monitoring systems often focus on a limited number of signals. A frequent focus is on eye movements (e.g., for eyelid closure or gaze direction), or brain waves (EEG recordings), but other systems have also tried to use head nodding, heart rate, core body temperature (Stork, 2012), skin conductance and facial expressions.

With the introduction of computer vision, systems have often become more diverse in the information that they deduce from driver activities. Computer vision systems often try and detect a range of behaviours such as blinking, yawning (Saradadevi & Bajaj, 2008; Sundelin et al., 2013), phone use, smoking, eating or drinking, which they then combine using machine learning techniques into a single estimate of fatigue or distraction. The advantage of computer vision systems is that they therefore monitor both for fatigue and distraction, while systems using other driver signals mostly focus on fatigue.

A further advantage of continuous operator monitoring systems is that they monitor fatigue and distraction in real-time or near real-time. Many also predict fatigue before incidents happen (Kerick et al., 2013). Eye movement measures and computer vision analysis of the driver have the additional advantage that they provide a direct measure of distraction, while for EEG recordings the link between external distraction and signal is less clear (NHVR, 2019). While head nodding may be used to detect the onset of sleep in drivers, warnings may occur too late, when successful intervention is no longer possible (NHVR, 2019). Moreover, head nodding may not occur for micro-sleeps, and to distinguish head nodding due to sleep from head nodding for other reasons

(e.g., checking the speedometer), relatively large amplitude nodding movements are often required.

Disadvantages of equipment to continuously measure signals of fatigue include its often intrusive nature, particularly if it requires wearing equipment (Kerick et al., 2013), or it may not be acceptable for workers due to privacy concerns (e.g., camera systems that face the driver and perform the analysis of the images offline in a cloud environment, often storing images for further development of the system). Furthermore, not all measures will reliably detect distraction (e.g., EEG, heart rate, body temperature; NHVR, 2019). A further consideration is that high false alarm rates, though not unique to driver monitoring devices, may cause drivers to ignore or even disable the device (Hartley et al., 2000).

1.3.2   Driving performance

Besides monitoring the driver, systems can also monitor driving behaviour. Interestingly, such systems have already been implemented in cars, often without independent evaluations of whether such systems detect fatigue and distraction with sufficient accuracy (Dawson et al., 2014).

Several studies, however, have suggested that performance-based measures may be used to detect fatigue in drivers. For example, braking events have more often been found with increased levels of fatigue (Mollicone et al., 2019). Likewise, lane crossing, corrective steering movements and pedal movements have been found to be associated with fatigue (Mortazavi, Eskandarian & Sayed, 2009; for an overview, see Kang, 2013).

Some performance measures may also indicate distraction. In a driving simulator study, it was found that distraction led to driving at lower speeds and increased difficulties in minding the current speed limit (Horberry et al., 2006). Distracted drivers were also found to brake more strongly and display more erratic steering movements (Donmez, Boyle & Lee, 2006). Likewise, a higher variation in accelerator pedal position and slower and more variable driving speed were found in distracted drivers (Rakauskas, Gugerty & Ward, 2004). Another study found increased variability in the position within the lane in distracted drivers (Crandall & Chaparro, 2012). A review of studies found that mobile phone use led to increased steering wheel movements, delayed braking, and reduced scanning of the surroundings (Oviedo-Trespalacios et al., 2016). When pooled together performance-based measures were found to predict driver state (no cognitive distraction, low distraction, high distraction) with a 74% accuracy (Jin et al., 2012). Not all studies, however, find an effect of distracted driving on driving performance. For example, Harrison & Fillmore (2011) found no such effect in sober drivers, and only found effects in alcohol-intoxicated drivers.

The advantage of driving performance measures is that their measurement is less intrusive than that of operator behaviour and as a consequence driving performance monitoring may be more acceptable to drivers, because the focus is on the task and not the driver (Dawson et al., 2014). Moreover, there is often no requirement for the driver to wear sensors, and use can be made of already existing internal sensors in the vehicle. The downside of the use of driving performance measures is that they intervene at a relatively late stage of fatigue or distraction (e.g., when the car starts to drift to the other lane, it may be too late to prevent a road crash). Also for these systems, frequent false alarms may make drivers ignore the warnings or disable the device (if possible).

Both driver monitoring and driving performance monitoring systems carry the risk that drivers may adjust their behaviour to the devices. Because devices provide real-time feedback, drivers may be tempted to set off when fatigued, because they may think that they can rely on the devices to keep them awake and safe. A Dutch review of driving performance monitoring systems suggested a low risk of such adaptive behaviour (Vlakveld, 2019). It is unclear whether these

findings extend to driver monitoring systems, which more directly monitor drivers' fatigue, and therefore may provide a stronger sense of the device helping them to keep awake.

1.4   Machine learning

Many of the recently introduced devices make use of artificial intelligence (AI), machine learning (a subset of AI) or deep learning (a subset of machine learning). Such methods allow for an improvement of the performance of the device when new information (e.g., video images prior to a road crash) comes in, and adjustment of the system to individual drivers (using signals from those drivers). The method used by many of these systems is supervised learning (James et al., 2013), where the system is trained with data with category labels (e.g., whether drivers were fatigued or alert, or whether they were eating, drinking, using their phones, or were alert). Training data for such learning are obtained by collecting sensor data and simultaneously recording the driver's state. Here, it is important to have a good method of measurement of the driver's state r, because the system's performance will be determined by the quality of this method. Obtaining such a measurement is not obvious: subjective fatigue, for example, is not always a good measure of actual fatigue, some tests take time and effort (such as the psychomotor vigilance test – PVT) and cannot be performed during driving, and no single type of alternative measurement (e.g., EEG) is 100% accurate.

1.5   Previously recommended systems

Past reviews have sometimes made recommendations regarding promising systems. In our review, we have found that some of these systems no longer seem to be available, and some systems may have been overtaken in terms of performance by newer systems, and therefore not all these former recommendations will be relevant. A comparison of past recommendations will also inform about how consistent reviewers are in their recommendations.

In the summary of their review Kerick et al. (2013) list ASTiD, Optalert and Safetrak as promising systems to start building a comprehensive fatigue management system. Mabry et al. (2019) list SmartCap, Guardian, and Optalert as validated, and LUCI, Drover Fatigue Alarm StopSleep, Smart Eye Antisleep and Bioharness as promising. Dawson et al. (2014) indicate that PVT, FIT, OSPAT, Safety Scope, Optalert, Copilot, Seeing Machines (Guardian), SmartCap, B-alert, and to a lesser extent Safetrak have good or reasonable validation support.

Across these sources, Optalert and Safetrak are recommended, and some support for Seeing Machines' Guardian is given. The list of devices in each report, however, does not seem to cover all devices that we have found. Whether the Copilot and Safetrak systems are still available, is unclear. Communication with Biopac on the Bioharness system appears to suggest the system is not ready (and will not be ready in the near future) as a fatigue detection system, and our own review may therefore yield results that are different from those in earlier studies.

1.6   This review

There is a strong interest in devices for fatigue and distraction detection, which is partly driven by the huge cost of fatigue and distraction related incidents (both human and financial) and partly by upcoming regulations on systems that need to be implemented in newly built cars. For example, in 2021 the EURO NCAP (www.euroncap.com) assessments for personal vehicles will include a 'driver monitoring' requirement, although it appears that it still needs to be specified what this will exactly involve. The interest in the topic is also reflected in the number of reviews that can be found, both in the scientific literature (Barr et al., 2005; Dawson et al., 2014), but also as internal

reports (Kerick et al., 2013; Mabry et al., 2019; NHVR, 2019). With several reviews already being available, it is important to indicate how the current review differs from existing reviews.

Past reviews have often focused on describing general system properties and classifying systems in different categories, examined the level of evidence for a product, or described a limited number of products in detail. For example, Dawson et al. (2014) rate a large number of devices, but focus specifically on evidence of the system's validity, and less on other aspects that may be of interest for fleets wanting to implement the systems, such as cost, acceptability and availability. Kerick et al. (2013) focus on the general principles of various systems. A listing of devices is provided at the end of the review, but without information on how each system scores on various criteria of importance. Mabry et al. (2019) provide more detail on various devices and include aspects such as cost, robustness and acceptability, but describe a relatively small number of devices. The present review aims to complement these reviews by focusing less on the general principles of the various systems (as these have already been extensively reviewed) and more on how the various systems score on the various criteria that may be of importance for those wanting to apply fatigue or distraction detection systems.

This report will continue as follows. A method section (*Chapter 2*) will describe how the list of devices and products was compiled and how information about the devices was gathered. The 'overview of devices' section (*Chapter 3*) will then describe each of the devices and the extent to which the devices meet the criteria and why. In this section, devices are grouped according to their main principles, which are briefly described and discussed at the start of each section. The discussion will then describe the recommendation for the field study and the reasons for this recommendation (*Chapter 4*). The *Appendix* lists the devices that did not make it to the main text, because they were no longer available, were still very much in the development stage, because insufficient information could be found, or because they tested something else than fatigue or distraction.

2 Methods

2.1 List of devices

A list of devices was compiled on the basis of three main sources: (1) Existing reviews of fatigue and distraction systems (e.g., Mabry et al., 2019; Dawson et al., 2014; Kerick et al., 2013), (2) companies who contacted the commissioners of this review with their products, (3) a Google search for devices, specifically focusing on distraction detection (as most devices from channels (1) and (2) were dedicated to fatigue detection). Some additional devices were added if they were suggested by colleagues or suppliers (e.g., when after enquiring about one device, a more appropriate device was recommended). Given time constraints and the sheer number of devices available, the present review may not be exhaustive, and it is therefore still possible that the long list of devices does not cover the entire market, or may not include recent additions.

The first focus of this review are the devices brought forward by the commissioners of this review. These devices are all described here, either in the main text or in the *Appendix* (e.g., when the device does not seem to be commercially available yet, no longer seems to be commercially available, when it was not described in sufficient detail in web-sources and the supplier did not respond to requests for information, or focuses on something else than fatigue or distraction detection, such as THC detection). The *Appendix* also contains devices often cited in past literature reviews, but that no longer seem to be commercially available. The decision on whether to include the device in the main text or the *Appendix* was somewhat subjective in that some devices in the *Appendix* could have been included in the main text or vice versa. The recommended devices are all in the main text.

After adding devices brought forward by the commissioners of this review and adding devices from other channels (e.g., past reviews), the descriptions of devices were reorganised in such a way that devices that used a common underlying mechanisms (e.g., EEG measurements, heart rate monitoring) were placed in the same section. Some devices used more than one type of mechanism and were placed on what seemed the dominant input used for fatigue or distraction detection.

2.2 Sources for assessment

The assessment of the various devices was based on a range of sources. Most commonly, the information on the website of the supplier and information provided by the commissioners of this review were considered first. This was often followed by a search of the scientific literature for evidence supporting the system, or evidence supporting the underlying principle of the system. This search was most commonly performed using Google Scholar, but also used citations of existing reviews. If no such information was found, the search for evidence was extended by using Google's main search function. This step also involved searching for user reviews, particularly for lower cost systems that can be purchased from more general vendor websites

such as amazon.com and alibaba.com. If the website of the supplier contained contact information that allowed filling out a contact form, or sending an e-mail, suppliers were contacted in this way. On various occasions, suppliers were hesitant to provide certain information, and offered to phone instead. This was followed up in several instances, but phone appointments did not always succeed and setting appointments was often difficult due to time-zone differences. Other common sources of information for our assessments were newspaper articles, blogs, YouTube videos, and forums discussing the various devices. In the descriptions, we attempted to indicate our sources as clearly as possible.

The assessment of the various devices is based on the combination of these sources. We spent a reasonable amount of time extracting relevant information for each device, but sometimes there was very little information that was gained through the various sources and the assessment may not be fully accurate in reflecting each enterprise's own assessment of their device.

One recommendation that arises from this review for the suppliers of the various systems is to be more open about the product that they are offering. If a large amount of effort needs to be spent on obtaining information about a system, this may not encourage interested parties to get in touch for a demonstration. Interestingly, the bigger players in the computer vision market appear to be quite open about their products (although keeping details about field studies and costs restricted). For example, Nauto provides a detailed blog with information about the general concepts and ideas behind the system. Seeing Machines provides several video interviews with users and is open about possible acceptability issues. Eyesight gives detailed information about what information is extracted from the images, and presents videos showing real-time detection of events. As peer-reviewed literature often lacks information about these systems (maybe because they are relatively new), such detailed information from suppliers can be expected to increase confidence and thereby market interest. When considering such evidence from suppliers, however, one has to keep in mind that the goal of the supplier will be to sell their product. Independent evaluations will therefore trump information from suppliers (the present review saw at least one instance: the EDVTCS system, where independent evidence did not support the findings of the supplier).

2.3   Device criteria

An important criterion for a device is that it accurately detects fatigue or distraction, but this is not the only aspect to consider when choosing a system to implement in a fleet of vehicles. Further considerations will depend on the sector, setting and personal user wishes. For example, for applications in the army, there will be additional or different criteria than for use in cars in regular traffic. In such a setting, a device should not impair drivers to quickly leave the vehicle, pose problems during evasive manoeuvres or near-crashes, and should not require installing special steering wheels or seats (Kerick et al., 2013). While for personal vehicles such criteria are also important, they may not be critical in the decision whether or not to adopt a system.

Whether a device will score high on a criterion also depends on the settings in which the device is likely to be used. For example, lane detection will only work well when there are lane markers. Therefore, if most of the driving is done in rural areas, a lane departure system may not work well. Likewise, eye tracking devices may not work well in situations where lighting conditions change rapidly. Whether to adopt a certain system may also depend on personal preferences. Some people may be comfortable with wearing a cap for EEG detection, or a wrist band for measuring sleep patterns, while others would not be willing to accept such devices. The issue of acceptability will be discussed in more detail after the general criteria have been introduced.

2.3.1 Criteria used in this review

Across sectors, settings and users, there are some criteria that are likely to hold in general. These are the following, which we will consider for each device in this review.

1. Validity

The device should respond when the person is actually showing signs of fatigue or distraction. Devices that provide too many irrelevant warnings (too many false positives) are likely to be switched off by the driver. Devices that miss too many drowsiness or distraction events (misses) are unlikely to reduce the number of incidents. To evaluate this aspect, this study considers evidence from peer-reviewed scientific literature, results from field studies, case studies, and user reviews.

2. Intrusiveness

A device that interferes strongly with the driving or the driver is likely to be abandoned. As indicated by Kerick et al. (2013), for the military, intrusiveness is particularly important, but generally, a device that distracts from driving or is likely to block the driver's view is not likely to be adopted for long. Ideally, the device should not involve extensive installation of equipment. There will be some overlap with the acceptability criterion below, as devices that need to be worn are more likely to be intrusive, and also more likely to be less acceptable.

3. Availability

The scientific literature presents a large number of prototypes of devices, or tests general principles of fatigue and distraction detection. There are also several start-ups seeking funding for development of their product ideas. Such devices, products and ideas, while possibly promising and important in future technology, may not serve businesses looking for a solution in the short term. This study therefore also considers which development stage the product has reached, and how long the product has been on the market, and whether there are signs of continuous development and evaluation, and whether customer support is provided.

4. Robustness

Evaluation studies are often performed in the lab, and tend to use driving simulators. For use in real-world situations, however, it is also important to consider how the device functions under different conditions. The robustness criterion will check whether the device works for different drivers, and under different driving conditions. Ideally, a device should be robust against environment influences such as heat, dust, humidity, impacts and road and lighting conditions, and differences between drivers (e.g., head size, use of prescription, safety or sun glasses, eye-pupil diameter, skin tone, or overall height).

5. Acceptability

For a system to be used in a large fleet of vehicles, it should be acceptable to most drivers. Devices that need to be worn, or interfere with driving may score low on this criterion, but also devices that record the driver and send the information into the cloud for further processing may cause privacy issues and be less often accepted. Some of such concerns may be addressed with driver education (e.g., about the risk and consequences of road crashes, about how video footage can also be used to their advantage, and assurances that the information is stored securely).

6. Sustainability

A device that needs to be charged frequently, that needs replacing or repairing frequently, or may be on the market for just a limited amount of time may be of less use than devices that score better on such aspects.

7. Cost

For a large-scale system implementation, the device should not be too costly. Costs to consider are for purchasing the system, any subscription fees or maintenance plans, or costs for repairs

and replacements. When inquiring about cost, we have also inquired after the cost for implementation in a largish fleet (more than 50 to 100 vehicles), as substantial reduction in cost can occur for larger scale production.

8. Compatibility
The system should not interfere with other systems inside the vehicle, such as communication devices, or navigation systems. This criterion specifically focuses on other systems, but overlaps partially with the intrusiveness criterion.

2.3.2 Other considerations

Reviews also mention other possible criteria of interest. We will consider these in the product descriptions s, but not explicitly describe these for every product. For example, Hartley et al. (2000) indicate that further considerations are: (1) *Access*. Who gets access to the fatigue detection results? Only the driver? The employer? Law enforcement authorities? (2) *Incentives.* Should rewards be given for non-fatigued driving (or conversely penalties for fatigued driving)? (3) *Feedback.* For in-vehicle technologies (either driver monitoring or driving performance), how should the results be displayed to the driver? (4) *Conceptual.* What does the device measure? Vigilance, attention, alertness, microsleeps, hypovigilance, performance variability, vulnerability to error or a combination of these?

Dawson et al. (2014) further suggest that the system should measure fatigue in real time, be able to predict future fatigue levels, and be suitable for use in an industrial setting, and be portable. A further consideration would be how the device warns the driver when fatigue or distraction is detected. When using a visual warning, is it sufficiently salient to be detected? When using an auditory warning, is it loud enough to be heard, but not so loud as to startle the driver? Do warnings distract the driver from driving? If false alarms occur, are the warnings acceptable in the long run? Finally, in some contexts and settings, users may prefer the device to be portable, so that it can be moved between vehicles and work environments (e.g., for use in an office setting).

2.4 Acceptability of wearable devices

This section elaborates on one of the device criteria listed in the previous paragraph: acceptability. While searching for user reviews for certain products, this criterion was found to be important. Devices can be highly accurate, but if drivers do not accept them, the device is likely to be ignored or disabled. Acceptability of devices may be compromised if users are required to wear them. Such wearable sensors (e.g., smartwatch, earpiece, wristband) are referred to as 'physiolytics' (Mettler & Wulf, 2019). Several studies have investigated under what circumstances wearing such instruments is acceptable and what may be barriers towards acceptance of such devices in the workplace. Knowing about these may aid the education of workers and selection of a device. In particular, studies seem to suggest that distinguishing between different workers and possibly offering different alternatives may improve acceptability of the devices. We here provide a short overview.

Using survey data from 120 workers, Choi, Hwang & Lee (2017) found that perceived usefulness, social influence, experience with wearable sensors and perceived privacy risk are important acceptability factors. A further study found that (1) workers often own a wearable sensor device, (2) around half of the workers say to be in favour of using a wearable sensor at work to track risk factors, and (3) employers would be willing to spend around $65-$80 per worker for such technology (Schall Jr, Sesek & Cavuoto, 2018). This study also found that barriers were concerns about privacy, compliance and sensor durability (Schall Jr et al., 2018). Mettler & Wulf (2019) also indicated privacy concerns, as well as concerns about personal freedom, technology dependence and individuality. The same paper also suggested not to treat all workers in the same way, as some more easily accept sensors than others. In order to distinguish workers, the authors

suggested to divide workers in different categories, such as individualists and balancers (Mettler & Wulf, 2019). A similar dependence on the worker was observed by Jacobs et al. (2019), who put forward a series of recommendations for employers wishing to implement wearable technology in the workplace. The recommendations included a focus on how the device could improve workplace safety, on the advancement of a positive safety climate to ensure that workers accept that the wearable device will meet the safety objective, and on how to involve the workers in the selection and implementation of the device(s) (Jacobs et al., 2019). Further concerns that were identified by Reid et al. (2017) included concerns about cost, confidentiality data, lack of demonstrated utility, and information overload.

2.5   Scoring

This study evaluates each device on eight criteria as described in *Section 2.3.1* (validity, intrusiveness, availability, robustness, acceptability, sustainability, cost and compatibility) using a five points scale – –, –, +/– , + and ++). For all criteria the author produced a rating, based on the available evidence, with one exception: When no cost information could be obtained 'NA' is listed, because, in contrast to the other criteria, absence of cost information could not be compensated for by considering images or descriptions of the device. For the validity (and robustness) criterion, the score reflects a combination of how much evidence was available, the quality of the evidence, and how much the evidence suggests that the device works for fatigue and distraction detection. Instead of scoring each of these criteria separately, descriptions of the evidence are described to support the scores given on these criteria. For the remaining criteria, information and evidence could be absent, just as for the cost criteria. In such cases, the score is based on the assessment by the author (e.g., while descriptions of devices will give some indication of whether a device will interfere with driving, absent information about the cost will not permit such type of assessment). The scores for each device are based on the evaluation by the author of this document and should therefore be taken as global indicators of how well the device matches the criteria, rather than as exact quality measures. For a similar reason, plusses and minuses are used rather than numbers to indicate the scores, to avoid any temptations to compute overall scores. Whether a device can be recommended will not depend on a strict sum of the scores. For example, if a device is not acceptable to drivers or not available, high scores for validity are unlikely to compensate for this.

3 Overview of devices

This section describes the fatigue and distraction detection devices for which sufficient information was found to compile an assessment on the eight criteria described in *Section 2.3.1*. The devices are organised according to the main principle that they appear to use. Each of the thirteen resulting sections begins by briefly describing that principle and its use in fatigue and distraction detection. Each section further contains a table scoring the various devices on the eight criteria.

3.1 Heart rate measurements

Heart rate and heart rate variability is used by some devices to measure fatigue (distraction is not detected by such devices). An overview of studies that show a link between heart rate and heart rate variability (HRV) with fatigue is provided by Mabry et al. (2019). These studies show that heart rate decreases during prolonged night driving and monotonous driving. Heart rate variability is associated with higher levels of fatigue and lower levels of driving performance. A complicating factor in using heart rate and HRV may be that while heart rate decreases and HRV increases with fatigue, completing mentally complex tasks has the opposite relation with higher heart rates and lower HRV (Mabry et al., 2019). Heart rate and HRV also vary with the circadian rhythm (VandeWalle et al., 2007), but this could be seen as a possible means to test for fatigue.

In direct tests of how well HRV predicts fatigue, Egelund (1982) found that HRV correctly predicted fatigue in around 90% of the cases (Patel et al., 2011), drowsiness (not necessarily due to a lack of sleep, but also for example caused by medication) in around 95% of the cases (Vicente et al., 2016), but sleepiness (due to a lack of sleep) in only around 60% of the cases (Vicente et al., 2016). Similar results were found by (Li & Chung, 2013) in a wavelet and support vector machine analysis. Three concerns are to be taken into account when interpreting these results in the context of commercially available devices on the basis of heart rate or HRV: (1) Is the sampling rate sufficient to reliably measure HRV? and (2) Is a false positive rate of around 5% an acceptable rate for users? (3) Under real-world driving conditions, are other factors at play that can influence heart rate in the driver? In order to reliably measure HRV, one of the suppliers suggested to aim for a sampling frequency of at least 250Hz.

Table 3.1 provides an overview of the devices using heart rate or HRV to detect fatigue. While some of the devices have been extensively evaluated for their ability to measure heart-rate, it is less clear how well they would perform as a fatigue detection device under real-world driving conditions. Overall, compared to other types of devices, heart rate systems do not seem to be an obvious choice for distracted driving and fatigue detection, because (1) they require skin contact for accurate measurements (higher intrusiveness and lower acceptability), (2) their reliability under real-world driving conditions is unclear (lower on robustness), (3) they do not detect distraction (other systems fail to do so as well, such as EEG systems, but are better at detecting fatigue). From the four devices considered, the Canaria system is probably the first device to consider, despite a lack of information about its accuracy and indications that it may still need some development before it can be implemented. For the two Holux devices it is unclear

whether they are still on the market, whereas for the Warden system it is unclear whether it will work without skin contact.

*Table 3.1. Scores of devices based on heart rate or heart rate variability*

Device	Validity	Intrusiveness	Availability	Robustness	Acceptability	Sustainability	Cost	Compatibility
Warden	–	+/–	–	–	+/–	–	NA	+/–
Holux DFD-100	+/–	–	–	–	–	–	NA	–
Canaria	–	+/–	–	+/–	–	–	NA	–
Holux WRL-8110	–	+/–	–	–	+	–	NA	+/–

3.1.1 Plessey Warden driver alertness monitor

The Warden driver alertness monitor (www.astute.global) makes use of a range of sensors placed on the driver seat (*Figure 3.1*) to measure the driver's heart rate. The website (www.astute.global) suggests that heart rate measured with the system provides an earlier warning of drowsiness than can be provided by eye or head movements. The device is said to measure heart rate and HRV without the need of skin contact. Whether this is a valid claim is unclear. There are some developments in contactless ECG systems (Sandra et al., 2014; Wu & Zhang, 2008), but there still seem to be few applications due to issues with poor signal quality and motion artefacts (Ottenbacher & Heuer, 2009; Wartzek et al., 2013; Wu & Zhang, 2008).

Whether the system is still available is also unclear. Links to the Plessey website (plesseysemiconductors.com) do not work. No further details, other than the information on the Astute Global website could be found. The system is described in Subramaniyam et al. (2018) and listed by NHVR (2019), but no further details about its operations can be found.

Figure 3.1. Images of the Warden system (from Szeszko (2017) and www.astute.global)

(a) Positioning

(b) General setup
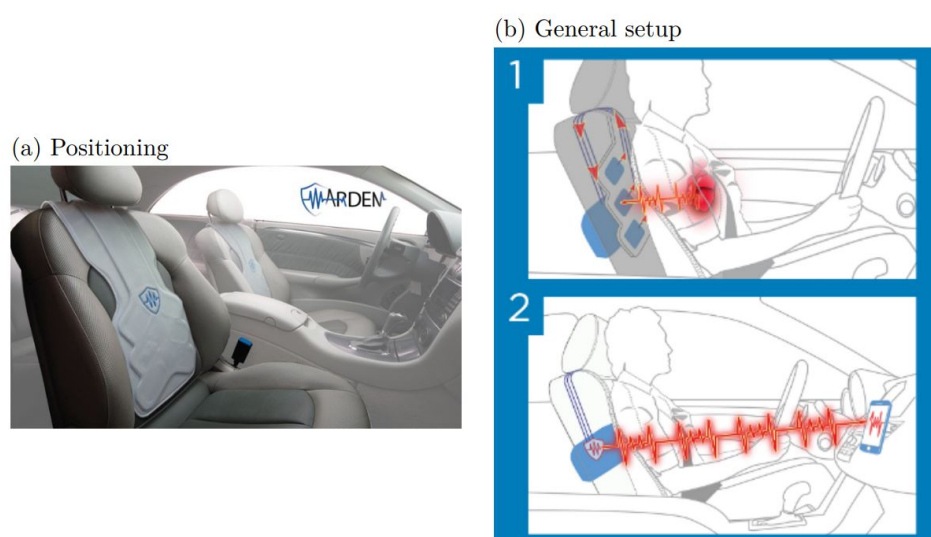
Validity
No evaluations of the system could be found. There is also little evidence that the underlying principle, contactless ECG measurements, works reliably (Ottenbacher & Heuer, 2009; Wartzek et al., 2013; Wu & Zhang, 2008).

Intrusiveness
The system needs to be placed on the driver seat, and is therefore less intrusive than heart rate systems that require skin contact. It does require fitting some equipment inside the vehicle.

Availability
It is unclear whether the system is still available. Links on the Plessey Semi-conductors no longer work.

Robustness
The system is likely to suffer from the driver's movements, and can be expected to perform worse for drivers wearing thick clothing.

Acceptability
Acceptability will depend on how comfortable the system is to sit against, and the rate of false alarms it produces. No information about either aspect could be found.

Sustainability
It is unclear whether the system is still on the market, or how long it would still be available. It is unclear whether the system would require maintenance or charging of batteries.

Cost
No information could be found on the cost of the system.

Compatibility
The system consists of a unit to be placed against the driver seat and an app on the phone, to be placed inside the cabin. Compatibility will depend on other systems needing to be placed at these locations.

3.1.2   Holux Hypo-Vigilance DFD-100

Two devices appear to have been developed under the name 'Holux': One that makes use of a unit to be attached to the seat-belt (described here) and one that makes use of a smartwatch (described later). The first device, the DFD-100 hypovigilance device from Holux technology inc. (based in Taiwan) is a module to be attached to the seat-belt below the sternum (see *Figure 3.2a*). It consists of a small unit (*Figure 3.2b*) with a rechargeable battery that emits a series of tones when it picks up signals consistent with driver fatigue. The user manual indicates the system has an accuracy of 90% and a false positive rate of less than 1% (meaning a higher false rejection rate, given the accuracy), but it is unclear under what testing conditions these results were obtained. A Google search for the company's website does not return results, and it is unclear whom to contact for further details or where to order.

In Google Scholar, a patent application for the device (granted 2015-09-22) can be found (Tao, 2015). The patent talks about measuring 'a plurality of physiological data' without specifying what these are. It then indicates to compute a 'feature curve' and 'regression slope' on these data, without clear specification what these computations involve.

The next step involves checking whether a 'first condition' (unspecified) is met (the text later talks about a second condition), after which the user's fatigue level is determined (also unspecified). Another image suggests heart rate is used, measured at different sampling rates. A final image shows a human with two wires attached to the neck ('another embodiment of the present invention'). Together, the patent application does not provide sufficient information to evaluate the working of the device for fatigue detection.

Figure 3.2. Images of the
Holux DF100 device
(a, b, and c) and the Holux
WRL-8110 smartwatch
(described in Section 3.1.4)

(a) DF100: Positioning

(b) DF100: General setup

(c) DF100: Warnings

Do not use the device when you drive on urban road.

(d) WRL-8110

Validity

While the supplier provides measurements of accuracy (90%) and a false positive rate (less than 1%), it is unclear how and under what conditions these performance measures were obtained (e.g., in how many drivers, under which circumstances). The manual indicates that the system should not be used when driving on urban roads (*Figure 3.2c*), and not to wear heavy clothing while using the device. These recommendations suggest that the less than 1% false positive rates may not hold under all possible circumstances. In combination with an accuracy of 90%, the false positive rate under 1% suggests that many events of fatigue are missed by the system.

Intrusiveness

The system has to be attached to the seatbelt and it is unclear whether it causes friction by being positioned in between the seatbelt and the driver's skin. It needs to be positioned carefully, and may therefore require adjusting before each ride. The device itself does not seem to take up much space, but does require the driver to wear a seatbelt.

Availability

While a manual is easily found on the internet, no contact details for the supplier or a site where the device can be ordered, seem to be readily available

Robustness

The device needs to be positioned carefully, suggesting its performance may not be optimal otherwise. The manual also suggests not to use the device on urban roads, while wearing winter clothes, or when it is connected to the battery.

Acceptability

The requirement for exact positioning and instructions on the thickness of clothes to wear is likely to impair the acceptability of the system. There are fewer concerns regarding privacy as no data seems to be stored or transmitted by the system. The system provides an auditory warning signal, which can be switched off, and is suggested to have a false alarm rate under 1%, which will also benefit acceptability.

Sustainability

The system will need to be charged regularly (estimated battery life is 8 hours, with a charging time of 4 hours. The device will not operate while charging). No information seems to be available about how long the system will be available for purchase, how long it will normally be operational, or whether repairs are possible.

Cost

No information about cost was found.

Compatibility

By its positioning between the seat-belt and the skin of the driver, it will interfere with any other devices that need to be placed here (although not very likely).

3.1.3   Canaria

The Canaria (canaria.co.uk) system consists of an earpiece (*Figure 3.3a, b*) that monitors vital signs, such as blood oxygen saturation, heart rate, respiration rate, ambient gas, and temperature. The product was designed to be used by astronauts with the aim to be non-intrusive (while simultaneously changing clothes, sleep, or using headphones). The design has been submitted for US and PCT patents (information from the product website). To reduce the weight and size of the device, it makes use of wireless charging, in addition to a small battery (backup for around 1 hour; open.nasa.gov/innovationspace/canaria). Communication with the supplier indicates that the current prototype still needs to be worn as a device attached to a belt, as the battery for the earpiece is still under development.

To measure heart rate and blood oxygenation, an infra-red (IR) LED pulses light into the blood vessels behind the ear, and its reflection is picked up by a sensor and stored in memory before being sent with Bluetooth technology. The website indicates that a client-paid trial to test the ability of the device to detect fatigue was scheduled for mid-2018, but does not seem to say whether it went ahead or what the results were. It also refers to a Facebook page for more details, but this page does not seem to contain information that is not already on one of the two web-pages. The device cannot be found in a Google Scholar search, which suggests that no peer-reviewed reports have yet been published.

Contact via LinkedIn suggests that the device is still in the development stage. The current model consists of a small unit connected to a sensor attached to the earlobe (*Figure 3.3c, d*). A demonstration video shows that the device picks up fatigue due to exertion, but it is unclear whether this extends to fatigue due to lack of sleep or monotonous driving.

Figure 3.3. Images of the Canaria product

(a) Earpiece

(b) Placement

(c) Unit

(d) Ear sensor
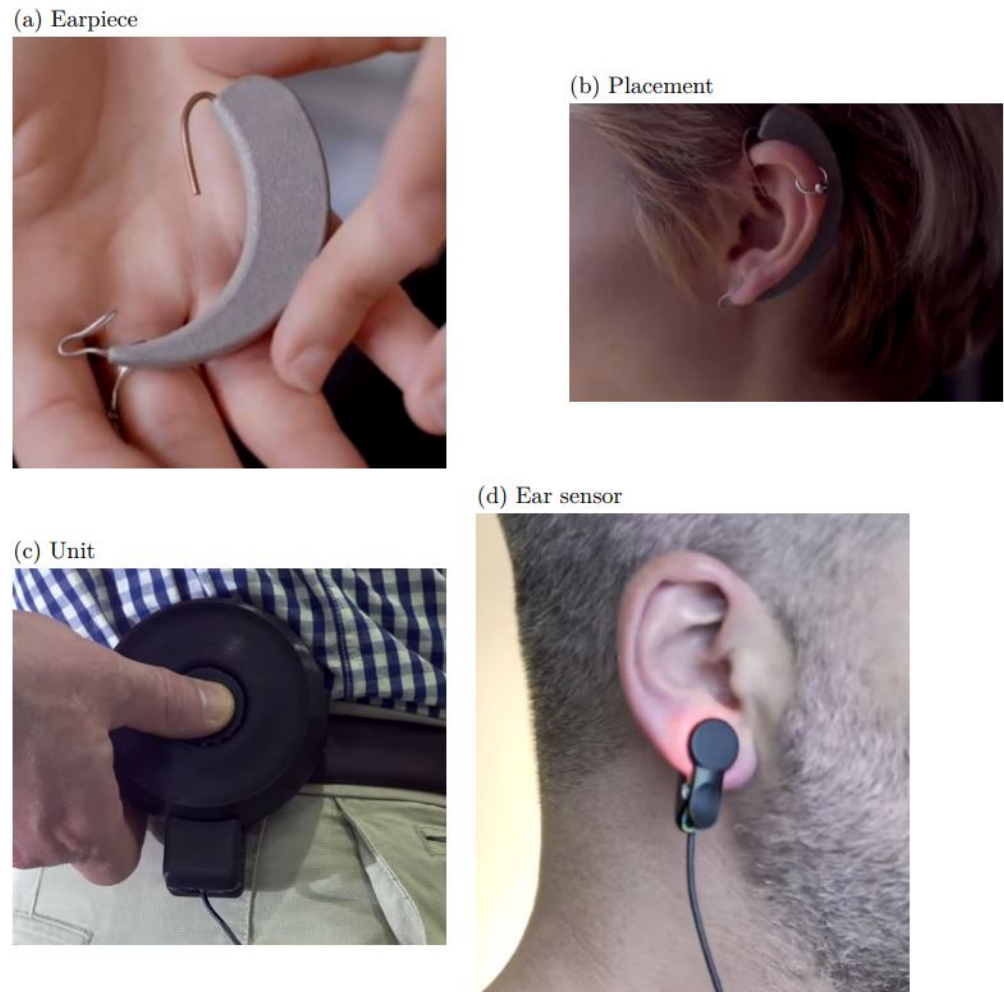
Validity

There does not seem to be documentation about how well the system works in a sample of users. From the description of the device it does not become clear what aspects of heart rate are being used, and therefore whether general findings concerning the link between fatigue and heart rate are applicable. The prototype device can be seen to detect fatigue due to exertion.

Intrusiveness

The website indicates that the system is comfortable to wear and that users forget they are wearing the system. No information about tests in a large sample of users seems to be available.

Availability

The system is still in the early stages of development and investment in the system would mostly be for its development.

Robustness

There does not seem to be any information available about how the system performs in a range of circumstances. A comparison of a strap band and an earpiece system suggests that heart rate can be detected reliably from an earpiece (Higgins et al., 2018). The prototype demonstrated in a video appears to be robust against movements.

Acceptability

As the system only uses an earpiece and no cameras, it may be acceptable to users as long as it is comfortable. The current version with a clip attached to the ear may become uncomfortable over longer periods of time.

Sustainability

Since this is a device that is still in the early stages of development, there is no information about how long it would be on the market for. The battery life is still under development.

Cost

No information about cost could be obtained.

Compatibility

The earpiece device may be incompatible with glasses, earplugs, or other earpieces worn for other reasons, although the website suggests it is compatible with headphones.

3.1.4 Holux WRL-8110

Besides the seatbelt unit described before, Holux technology inc. has also introduced a smartwatch (see *Figure 3.2d*), which makes use of a heart rate sensor (optical measurements), a G-sensor (acceleration) and a compass (direction), and provides auditory and vibrational output. An online presentation on the system indicates that its battery allows for 24 hours continuous heart rate monitoring, or a 60-day stand-by mode. The device can transmit signals to a Holux app, which can then be shared with a webservice and call centre. The smartwatch not only monitors fatigue while driving, but also sleep quality off work. The device will cost around $200. The documentation suggests that the device can interface with a Lane Departure Warning System (LDWS). Besides fatigue detection, the device will also warn for long operation times.

One of the commissioners of this review has suggested that the device was available several years earlier, but it is unclear whether it is still on the market at the time of writing this document. The company website does not seem to be accessible and the company only provides telephone and fax numbers, but not an e-mail address (making contacting the supplier from other time-zones more complicated).

Validity

No validation studies of the device were found in a Google Scholar or Google web search. In contrast to the DFD-100 device from Holux, no information about the accuracy or false positive rates could be found from other sources. The patent for the DFD-100 (Tao, 2015) suggests that heart rate, rather than heart rate variability is used for fatigue detection. Whether a smartwatch is the best method to accurately measure heart rate is uncertain. In a direct comparison between a wristband using a photoplethysmography (PPG) sensor and the gold-standard electrocardiography (ECG) sensor in a chest strap, an overall 0.85 correlation was found between the measurements with both types of devices, which decreased to 0.61 for heart rates above 110 beats per minute (Hwang et al., 2016). There were also indications for motion artifacts, which may make heart rate monitoring from wristbands only effective without movement of the operator.

Intrusiveness

Smartwatches are not very intrusive, unless other devices need to be worn around the wrist. Some workers may not like wearing them.

Availability

The supplier is difficult to contact and it is unclear how to order the device. The only information on the device was received indirectly, and no information can be found on the internet. There are no indications of other bigger players using the system.

Robustness

Studies of measuring heart rate with a smartwatch suggest that such devices may be susceptible to movement of the user. It is also unclear to which extent the measurements are affected by sweating.

Acceptability

Generally, activity trackers in the form of a wristband are well accepted, but this often involves the user actively choosing to wear one. It is less clear how acceptable wristbands are to people who may not wear one of their own accord.

Sustainability

Given the difficulties with availability, long term availability of the system is unclear. How long the system will work without needing to be replaced, is also unclear.

Cost

The device is expected to cost around $200.

Compatibility

The system will interfere with any other devices that need to be worn around the wrist.

3.2 Head nodding

Some older or lower-cost systems make use of head nodding to detect fatigue in the driver. Head nodding only occurs near sleep onset (Dawson et al., 2014), which may make successful intervention difficult. To distinguish between nodding and looking down for other reasons, a fairly large nodding angle will be needed.

The effectiveness of head nodding as a measure for fatigue was studied with the MINDS system. Results suggested that nodding due to microsleeps (as measured with an EEG system) was visible in the system's sensor data (Heitmann et al., 2001), but that some microsleeps occurred without head nodding, which therefore were not detected. Detailed information about accuracy and false alarm rates were not available from this study.

Consequently, head nodding on its own, without additional further information (e.g., eye closure) is unlikely to yield a reliable system for fatigue detection. Current computer vision systems (see *Section 3.4*) that also detect nodding therefore appear to combine information. Systems that just use head nodding appear to be mostly historical or very-low-cost systems. *Table 3.2* provides an overview of devices, suggesting evidence for the validity of such systems is limited. The devices also suffer from low acceptability, because they involve wearing something on one's head. Given that EEG systems, having the same disadvantage, are better validated for detecting fatigue, there is no clear argument for head nodding devices. Finally, the devices do not monitor for distraction.

Table 3.2. Scores of devices that use head nodding to detect fatigue

Device	Validity	Intrusiveness	Availability	Robustness	Acceptability	Sustainability	Cost	Compatibility
Co-pilot	–	+/–	+	–	–	+/–	–	–
Alert Me	–	–	+	–	–	–	+	–
Safeguard	–	–	– –	+/–	–	– –	NA	–

3.2.1 Co-pilot

Finding information about the co-pilot system was complicated by the fact that there appear to be three systems under that name. In Dawson et al. (2014), it refers to a device using a dashboard camera that measures PERCLOS, that has been independently validated (CoPilot/DD850). We will later (*Section 3.13.2*) describe this device as DD850. Mabry et al. (2019) refer to a system embedded in a headset (Maven co-pilot; see *Figure 3.4a*), making use of head movements, which has not been independently validated (Mabry et al., 2019). Lynley (2017) suggests that Nvidia is

working on a system that uses cameras and microphones to detect fatigue, which may have been launched in 2019 (Green Car Congress, 2019) although no website can yet be found that offers the product for sale. Below, we indicate how this commercially available headset system (Maven co-pilot, *Figure 3.4a, b*) scores on the various criteria.

The Maven headset is used in combination with a smartphone. Besides detecting nodding movements, it also detects speeding and braking of the vehicle, as well as mirror checking. The device is said to detect distraction by detecting up-and-down glances (Camas, n.d.). The headset also provides updates on the weather.

Validity
No information was found about validation studies of the device. Head-tracking in itself has not been shown to be a highly reliable method for fatigue detection, as (micro-)sleep can occur without head nodding. It is also unclear how reliable up-and-down glancing is as a measure of distraction from a mobile phone.

Intrusiveness
The system requires wearing a headset, which may be uncomfortable in the long run and interfere with driving.

Availability
The product is currently on the market. It can be ordered from the website mavenmachines.com/maven-co-pilot/.

Robustness
It is unclear whether the system is influenced by head movements.

Acceptability
The system does not monitor the driver, and is unlikely to yield privacy concerns.

Sustainability
There is nothing to indicate that the system will not be around for a long time.

Cost
Mabry et al. (2019) indicate the system costs around $99 to purchase, and around $30 per month (service charge).

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Compatibility

The system will not be compatible with other headsets or other headgear.

3.2.2 AlertMe

Figure 3.5 shows the AlertMe product. It is a small device (*Figure 3.5a*) to be placed behind the ear (*Figure 3.5b*) that will make a sound or produce a vibration when the driver starts nodding. The product is low cost ($6.66 at walmart.com or $6.60 at amazon.com). No scientific literature can be found on the device. Amazon.com lists 97 reviews, which are mixed (*Figure 3.5c*). Reviewers indicate the sound is too loud (or not loud enough), the device is uncomfortable, it will fall off your ear, it will not detect sleep that does not involve nodding, it will not detect sleep that involves nodding bending the head backwards, that extreme nodding is needed for the device to work, that the device is too sensitive (contrasting the previous reviewer), or the sound goes off when bending forward for other reasons.

Figure 3.5. Images of the AlertMe device

Validity

There does not seem to be a systematic evaluation of the device. Reviewers on Amazon indicate that it is uncomfortable, falls off the ear, does not detect sleep without nodding, gives too many false positives (e.g., looking at the speedometer), and is too loud.

Intrusiveness

The device needs to be worn around the ear. Users indicate the fit is not very good and the device keeps falling off.

Availability

The product can be ordered from the Walmart and Amazon websites.

Robustness

Reviewers indicate that the device is poorly built. It alerts the driver too often, or not often enough.

Acceptability

Reviewers do not mention privacy concerns with the device. Some indicate that the device is uncomfortable.

Sustainability

A lifetime of 30000 nods is reported. The duration of continuous standby time is unclear. How long the product will be on the market, is unclear.

Cost

This is a very low-cost device (around $6.60).

Compatibility

One Amazon reviewer indicates that the device is compatible with glasses. It will not be compatible with other devices that need to be worn around the ear.

3.2.3 Safeguard

The Safeguard (glass.mafic.ltd/) system is placed inside the hardhat (*Figure 3.6*) and its principal aim is to monitor the environment for hazards (heat stress, noise levels, welding fumes, hand and arm vibration), but e-mail contact with one of the commissioners of this review has suggested that the device can also measure fatigue by monitoring for head nodding. Further information from the website suggests that it uses deep learning to derive events such as slips, trips, falls, noise, welding fumes, and injuries from the data collected by the device. Exactly what kind of information is collected or how this information is collected (or how reliably) is not clear. The website does not mention fatigue, but e-mail correspondence has suggested this to be one of the events that can be detected.

Figure 3.6. Safeguard system
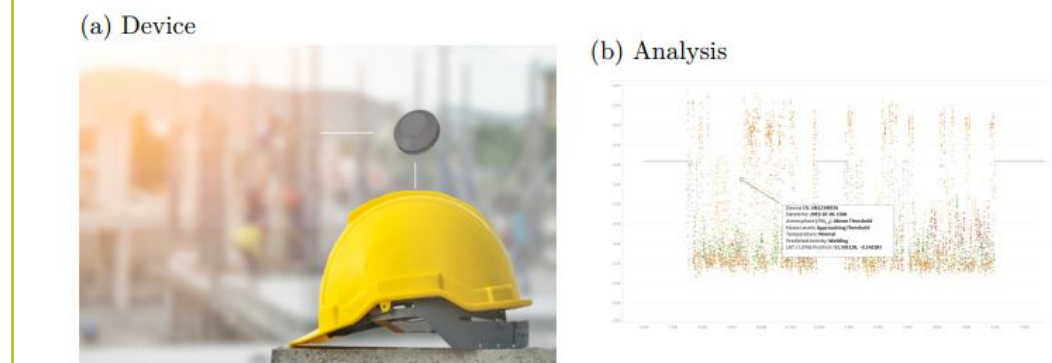
Validity

The website does not provide documentation about the effectiveness of the system, and no further information could be obtained from the supplier.

Intrusiveness

If the driver is already wearing a hardhat while driving, the system should not be intrusive (unless it is heavy; it does not seem to be large).

Availability

The system is still in an early stage of development. The website does not mention an application in fatigue detection, and this purpose was only clear from information sent by the review commissioners.

Robustness

For the system to work under different conditions, the sensor should be robust to head movements and humidity. No information is available about the influence of such factors.

Acceptability

The system is embedded inside a hardhat, which may be a concern.

Sustainability

The device is still in an early stage of development and information about long-term use of the system is not yet available.

Cost

The website does not provide an indication of the cost of the system, and an e-mail enquiry did not yield any information.

Compatibility

The system requires the driver to wear a hardhat, which may be intrusive (see above), and makes wearing other headgear difficult (if required).

3.3 Camera systems without computer vision

Most fatigue and distraction systems that use cameras also use computer vision. There are also systems that do not use computer vision technology, and detect safety critical events from other sensors and then submit the video materials to a control centre, where the footage is evaluated by a human operator. False alerts are less of a concern for such systems, because of human evaluation of the videos. The systems will be mostly beneficial for driver training and evaluation rather than for providing real-time warning signals for fatigue and distraction. *Table 3.3* provides an overview of these systems without computer vision. Because there are systems on the market that can analyse images directly without human intervention, camera systems without computer vision, while potentially beneficial for fleet management, will not be the preferred option for fatigue and distraction detection.

Table 3.3. Scores of camera systems that do not use computer vision

Device	Validity	Intrusiveness	Availability	Robustness	Acceptability	Sustainability	Cost	Compatibility
MTData	–	+/–	+	+	+/–	–	+/–	+
SmartDrive	+	–	+	+/–	–	+	NA	–
Lytx	+/–	–	++	++	–	+	NA	+/–

3.3.1 Complete fatigue – MTData

The complete fatigue system from MTData was found in the review by Kerick et al. (2013), who described the system as an hours-of-service monitor. Current information on the website (Telstra, 2019) suggests that the system also monitors driver behaviour and has an in-vehicle dashcam. Whether these new components provide real-time warnings for fatigue and distraction is unclear. The system mainly purposes to provide a tool that allows fleet managers to track vehicle locations. No scientific validation of the system was found, but the main website (mt-data.com.au) lists two case studies, both from 2016, one in the oil-and-gas industry and one in asset forestry. The first describes the 'hawk-eye' web-based software that can be used to track vehicles (no fatigue or distraction detection) and the use of g-Force sensors to detect harsh cornering and the use of an in-vehicle driver screen. In line with Kerick et al. (2013), the system appears to be mostly beneficial in terms of fatigue management by monitoring the number of hours that a driver is on the road.

Validity

Two case studies are mentioned, but no independent validation studies appear to have been conducted. It is unclear whether the system makes use of validated mathematical models or tests or whether it specifically tests for fatigue or distraction.

Intrusiveness

The system makes use of sensors already available in vehicles, with the exception of the dashcam (but this seems to be an add-on).

Availability

The website (mtdata.com.au) suggests the system has been around for several years. Two case studies from 2016 show that the device has been in operation.

Robustness

The system relies on the Telstra network (Telstra, 2019). Functionality will depend on the connection with this network. The system should work day and night, and under different weather conditions.

Acceptability

Drivers do not need to wear anything and no warnings are given real-time, which may make the system more acceptable. The system does allow fleet management to track the driver, so there may be privacy issues.

Sustainability

The Telstra network that the system uses, will be disabled in 2024, and it is unclear whether the system will work after this date (Telstra, 2019).

Cost

The cost depends on the version of the system. It varies between around 300 Australian dollars to around 5000 dollars per driver (Telstra, 2019). It is unclear how the two version of the systems differ, but the difference could be related to just a hardware option, compared to a full fleet management option.
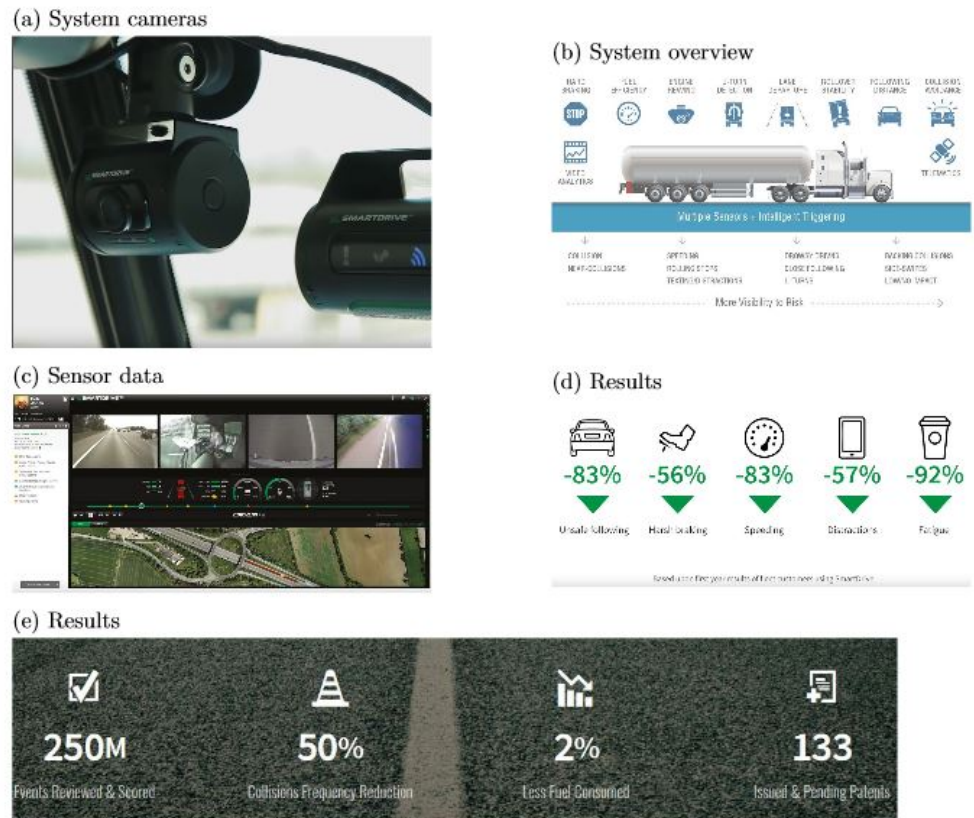
Compatibility

The system is unlikely to interfere with other systems in the vehicle.

3.3.2 Smartdrive

Smartdrive (www.smartdrive.net) is a hybrid system, in the sense that it makes use of cameras and in-vehicle sensors (*Figure 3.7*). It is aimed at (1) improving driving behaviour in drivers by monitoring and reviewing video materials and sensor data, (2) clearing drivers in case of road crashes that were not their fault. The system does not seem to be targeting fatigue and distraction in particular, but may be used in this context. No evaluation studies appear to be available, but there are videos of drivers describing how they experienced the system. One driver indicates that the system was set up so that he could earn additional income by meeting the safe driving standards. Another user indicates that a driver was cleared after a road crash, which may provide a reason for drivers to more easily accept the system. The system is supported by a large number of patents (Plante, 2015; Plante & Kasavaraju, 2013; Plante et al., 2008, 2012, 2014). The website has a large collection of video materials, a blog, case studies, white papers and data-sheets (one of these was ordered by entering detailed contact information, but was then found not to contain data).

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(a) System cameras
(b) System overview
(c) Sensor data
(d) Results
(e) Results

Validity

The videos on the website provide some numbers on the performance and testing of the system. They indicate that 250 million events have been scored and reviewed, that the system reduces the number of collisions by 50%, that the system leads to a reduction of fuel consumption of 2%, and is supported by 133 patents (issued and pending), see *Figure 3.7d*. Further numbers indicate an 83% reduction in unsafe following, a 56% reduction in harsh braking, an 83% reduction in speeding, a 57% reduction in distractions, and 92% reduction in fatigue. These numbers are said to be based upon first-year results of fleet customers using Smartdrive, without further reference to a document detailing the methods used to obtain these results. Google Scholar does not return relevant entries for the system other than the patents (e.g., Plante, 2015; Plante et al., 2014). A further presentation (SmartIQBeat, 2017) suggests that collision drivers were 41.1% more often talking on the phone (handsfree), 60.7% more often texting, and 60.6% more often yawning. These results are said to have been obtained by expert video analysis and observation scoring. Overall, there appears to be some evaluation of the system, but methods are unclear, and no independent studies appear to be available. The system will not provide real-time warning signals.

Intrusiveness

The system is not expected to interfere with driving. It will require the installation of some equipment (cameras, see *Figure 3.7a* and *Figure 3.7c*), and may therefore be difficult to transfer to a different vehicle.

Availability

The system can be ordered from the website (www.smartdriver.net). There is extensive documentation about current users, which suggests that the system has been around since at least 2012 (years in the 'in the news' section).

Robustness

The system appears to rely in part on the automatic processing of signals from the vehicle. It is unclear how robust this part is against adverse weather conditions or poor road conditions. The system requires the transmission of signals to a server, which may break down in case of poor internet connections.

Acceptability

The system requires the installation of cameras inside the vehicle, and the transmission of the images to an online system. This may raise privacy concerns with the driver. The website suggests that such concerns may be reduced by offering incentives (e.g., additional payments for good behaviour) and explaining that the images may help drivers be cleared from road crashes that were not their fault.

Sustainability

The website gives the impression that the system will be around for some time.

Cost

No information could be obtained about the cost of the system. An e-mail inquiry did not yield any further information. Because some human intervention is involved in processing the camera recordings, some form of subscription costs can be expected.

Compatibility

The system is likely to interfere with other equipment that needs to be placed in the same position as the cameras. The transmission of signals to the web servers may also interfere with other equipment that requires the bandwidth of the internet connection.

3.3.3 Lytx DriveCam

Drivecam is a system developed by Lytx (www.lytx.com) that uses a forward-facing camera and lane detection and a camera facing the driver (*Figure 3.8*). It does not automatically analyse the images, but instead sends the video recordings to a control centre. In order to detect sections that need to be reviewed, sensors inside the vehicle are used to detect strong forces on the vehicle (Cook, 2010). While this suggests that only video material related to such events is reviewed, drivers have suggested that video footage is sent more frequently (DiBellio, 2017; Trucking Review Channel, 2017). While this system does not continuously monitor for fatigue and distraction, the reviewed video materials can be used for driver training and awareness and therefore help prevent road crashes caused by these factors. Such a purpose is also supported by Davis (2011), indicating that video images are analysed by highly trained specialists, which can then be used for additional coaching or to reward appropriate driving behaviour.

Figure 3.8. The DriveCam system. Images taken from Davis (2011)

(a) Camera

(b) Footage

(c) Results

Reduced Risky Driving by more than 50%

Federal Motor Carriers Safety Administration

Validity

No peer-reviewed scientific publications were found that validated the Drive-Cam. The video (Davis, 2011) suggests that the Federal Motor Carriers Safety Administration found that the DriveCam leads to up to a 50% reduction in risky driving, up to 80% reduction in Dollars spent on claims, and up to 12% fuel savings.

Intrusiveness

Drivers find the DriveCam highly intrusive (Davis, 2011; DiBellio, 2017; Trucking Review Channel, 2017). Not only are there concerns that the system is mostly used to correct driver behaviour, but it is also produces a flashing light each time a video is recorded and transmitted to the control centre. One comment on the video goes as far as suggesting that the DriveCam has led to an excess death because of a driver distracted by the light (Davis, 2011).

Availability

The DriveCam has been used in various fleets and by various operators.

Robustness

Because the system makes use of trained human operators, it can be expected to be robust against differences in driver and road characteristics. The operators only have footage of two cameras, which may somewhat limit how well they can determine what happened in critical events.

Acceptability

The system is highly unlikely to be accepted by drivers. Some drivers indicate that they do not wish to drive for a company employing the DriveCam (comments in Davis, 2011). Cook (2010) suggests that by addressing drivers' concerns, the system may become acceptable.

Sustainability

The system can be expected to be around for a while.

Cost

No information about cost was found. An e-mail enquiry did not produce results.

Compatibility

The system requires the placement of two cameras, and may thereby interfere with other devices that need placing at these locations.

3.4   Computer vision

The emerging technology within fatigue and distraction detection is computer vision. In computer vision, computer systems analyse images, or series of images (video clips) for patterns (colours, gradients, textures, biological features) and objects (e.g., cars, people). Computer vision systems for fatigue and distraction have focused on (1) measuring driving behaviour using a forward-facing camera (e.g., to detect unexpected lane departures), (2) detecting driver fatigue or distraction using a camera facing the driver, or (3) using a hybrid approach and using measurements from both driving behaviour and driver behaviour.

The challenge of automatic detection, common to challenges faced by humans visually exploring the world, is the identification of objects and events of interest against noisy and cluttered backgrounds, subject to partial occlusion, and under different lighting conditions. Various visual illusions demonstrate that even for the highly specialised human brain, this is not a trivial task.

A common strategy to tackle computer vision problems, is not to try to cover every possible scenario, but focus on the image aspects important to solve the task at hand. Two common tasks in the context of fatigue detection are illustrated in *Figure 3.9*. The first example shows how computer vision may be used to detect unexpected lane departures (a sign of fatigued or distracted driving) by finding lane markings on the road as well as other relevant objects (cars, traffic signs). The second example shows the analysis of driver images that may signal fatigue or distraction, for example by looking for changes in head direction or closure of the eyes.

For lane detection, two main types of algorithms can be distinguished: (1) feature-based and (2) model-based, where the first method searches for local features in the image, and the second method tries to construct a (3D) model of the scene. Feature methods require clear lane-markings, and perform worse under sub-optimal conditions (e.g., fog, rain) and suffer from occlusions (e.g., a car passing). Model-based methods are more robust against less than optimal conditions, but may only work in specific contexts (Kaur & Kumar, 2015).

Figure 3.9. Computer vision for fatigue detection (source: YouTube)

For object detection using image sequences(which allows for the comparison of changes in subsequent images), five methods are distinguished: (1) frame differencing, (2) optical flow methods, (3) temporal differencing, (4) point detectors, and (5) background subtraction (Sukanya, Gokul & Paul, 2016).

In frame and temporal differencing, the difference between subsequent frames is computed to find moving objects (Zhang & Wu, 2012). Optical flow methods compute local changes in the direction of elements, a method also thought to be employed by the human brain (Authié & Mestre, 2012). Point detectors aim to locate meaningful points in an image. They can be used for detecting key points in face images (Berretti et al., 2011). Finally, background subtraction specifically focuses on separating the image in foreground and background.

Once objects have been detected, features of these objects, such as orientation need to be computed. One application involves algorithms to detect head pose. The challenge here is that accurate detection is needed under camera distortions, various lighting conditions, facial expressions and accessories like glasses and hats (Murphy-Chutorian & Trivedi, 2008).

Under the assumption that the head is a rigid object, the head direction can be described in three dimensions: pitch, roll and yaw. In addition to the direction of the head, one may also attempt to estimate gaze direction. Murphy-Chutorian & Trivedi (2008) categorise head pose detection methods in eight different categories: appearance template, detector array, nonlinear regression, manifold embedding, flexible models, geometric methods, tracking methods, hybrid methods (a combination of the other methods), which each have their advantages and disadvantages. Murphy-Chutorian & Trivedi (2008) list the hybrid methods as the most promising and suggest a solution that meets all their requirements (accurate, monocular, autonomous, multi-person, identity and lighting invariant, resolution independent, full range of head motion, real-time).

Other computer vision tasks that are relevant to fatigue and distraction detection are eye closure measurements (PERCLOS), further described in *Section 3.13*, detection of facial expressions and yawning movements, the detection of objects such as mobile phones, food, drinks and cigarettes, and the detection of other vehicles ahead of the driver.

Computer vision may be used with or without machine learning. Some computer vision algorithms work by analysing images without a learning stage. They may, for example, detect edges, coloured surfaces, or changes between subsequent images. Other algorithms require the presentation of a large number of examples for the class they need to detect. For example, the Haar classifier for object recognition is constructed by presenting a large number of positive (e.g., images with a face) and negative (e.g., images without a face) images to the algorithm, which then compares image features in positive and negative examples to construct a model that can classify new, unseen images (OpenCV, 2019). Many computer vision methods have been made available as an open source library (OpenCV, 2019; Bradski & Kaehler, 2008). Computer vision systems were found to be available from general computer vision companies, companies that specialise in driver monitoring and ADAS systems, but also in the form of low-cost devices (of around $200). A further distinction is the focus of the system. First, systems that use a forward camera only (searching for other vehicles and lane markings mostly; see *Table 3.4*) are discussed. This is followed by systems that use a camera facing the driver (looking for features such as eyelid closure, yawning, mobile phone use, see *Table 3.5*). Finally, hybrid systems are discussed that use forward and driver facing cameras (*Table 3.6*).

3.4.1 Road monitoring

Table 3.4 provides an overview of systems that monitor the road. The list is fairly short, as the original list for this review was, to a large extent, based on existing reviews, which do not always consider lane departure systems. From the three systems that made it to the list, the Mobileye system is the only one that is certain to be available.

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Table 3.4. Scores of computer vision systems that use a forward-facing camera to monitor the road

Device	Validity	Intrusiveness	Availability	Robustness	Acceptability	Sustainability	Cost	Compatibility
Mobileye	–	+/–	+	–	+	+	NA	+
Autovue	–	+/–	+/–	+/–	+	+/–	NA	+
Safetrak	+	+/–	–	+/–	+	–	NA	+

3.4.1.1 Mobileye

On their website (www.mobileye.com), Mobileye indicates to be a world leader in the development of Advanced Driver Assistance Systems (ADAS) and autonomous driving, employing a workforce of around 1,700 people. The system provides a broad range of features to assist drivers, including Automatic Emergency Braking (AEB), Lane Departure Warning (LDW), Forward Collision Warning (FCW), Lane Keeping Assist (LKA), Lane Centering (LC), Traffic Jam Assist (TJA), Traffic Sign Recognition (TSR), and Intelligent High-beam Control (IHC), all with a single camera mounted on the windshield (*Figure 3.10*). These features are not directly targeted at detecting distraction or fatigue, but may help prevent crashes when distraction or fatigue start to affect driving performance. The system makes strong use of computer vision algorithms to perform all these tasks. The system is not specifically designed to detect sleepiness or distraction, and instead focuses on detecting the effects of sleep on driving, such as unintended lane departures or collisions with other vehicles or pedestrians (Mobileye, 2019).

Figure 3.10. Mobileye system (source: YouTube)
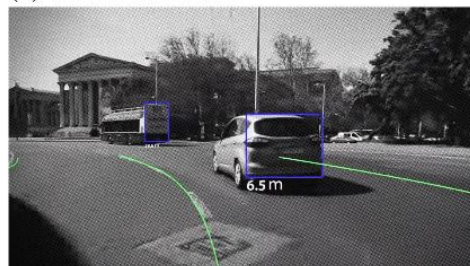
(a) Vehicle detection   (b) Pedestrian detection

Validity

No systematic evaluation studies of the system were found. Test results are classified due to the highly competitive market. The system was described by various reviews of devices (Dawson et al., 2014; Kerick et al., 2013; NHVR, 2019) without further indications of publicly available evaluations of the system. The system was also used in naturalistic driving studies (e.g., Bärgman et al., 2017). Case studies listed on the website (www.mobileye.com) suggest that the system can result in an 80% drop in rear-end collisions (Canada), an 80% drop in collisions overall (Japan), a 58.5% drop in vehicular and pedestrian collision claims (Washington state), a 30% drop in avoidable collisions, a 60% drop in passenger injuries (London), and a 5% decrease in energy consumption (Shanghai).

Intrusiveness

A single camera needs to be placed against the windshield. The system needs to be installed and calibrated by Mobileye, but can be moved from one vehicle to the next. It will work inside vehicles only. A small camera is installed behind the front window.

Availability

Although ongoing development is taking place, the system is available for purchase and has been applied extensively in various types of vehicles.

Robustness

Validation information on how well the system works under different road and driver conditions is not directly available. A low false alarm rate is reported by Mobileye without an exact number.

Acceptability

The system is likely to be accepted by drivers. Similar systems are already available in personal vehicles. The information is stored and processed locally, which increases the chance that the system will be accepted.

Sustainability

With a workforce of around 1,700, the system is likely to be around for the foreseeable future. As it is integrated into a vehicle, no issues with battery life are to be expected. There is no subscription fee, and the latest system versions can be updated.

Cost

The cost will depend on where in the world the device is purchased, the system version, and how many devices are purchased. For the device with a single camera, and for a largish fleet (> 100 vehicles), the ballpark figure is around $700 for a unit and $400 for installation and calibration.

Compatibility

There do not seem to be compatibility issues with other equipment.

3.4.1.2 Autovue

Autovue (www.bendix.com/en/products/autovue/) is a lane departure system, previously supplied by Iteris, but sold to Bendix in 2011 (Iteris, 2011). The system is said to work day and night and under most weather conditions. It provides a warning signal when the vehicle drifts across a lane marking, without the driver having indicated a lane change (Sullivan et al., 2010). Past reviews cited no validation studies (Dawson et al., 2014; Kerick et al., 2013). Sullivan et al. (2010) suggested the system depends on computer vision and may therefore perform worse under poor lighting conditions and occlusion.

Validity

No evaluations of the system could be found.

Intrusiveness

The system relies on a forward-facing camera. It is unclear where this camera needs to be mounted and whether further equipment needs to be installed.

Availability

The system is described on Bendix' website, but little information on either the system, or how to purchase, is provided.

Robustness

The supplier indicates that the system should work under day and night conditions and under adverse weather conditions. Sullivan et al. (2010) suggest that, because the system relies on computer vision, it may be susceptible to poor lighting conditions and occlusion.

Acceptability

Generally, lane departure systems are well accepted.

Sustainability

The Autovue system has been sold to a new supplier (Bendix; Iteris, 2011), who will apparently continue the product.

Cost

This information was requested but not obtained.

Compatibility

It is unclear how much equipment is needed for this system, but not much interference with other devices is expected.

3.4.1.3 Safetrak

The Safetrak system from Takata Corporation (Tokyo Japan) uses a forward-looking video camera and video processing to monitor for lane deviations, inter-vehicle distance, and time-to-contact (Kerick et al., 2013). The company and the system are described on various websites, including Wikipedia, but the main website, www.takata.com (link from the Wikipedia-page), cannot be reached. Kerick et al. (2013) mention two system evaluations, one by the company itself, and one by the U.S. department of transportation. Both are said to have found an approximate 50% decrease in lane departures, an approximate 20% decrease in single-vehicle road departure crashes and an approximate 24% decrease in rollover crashes. Dawson et al. (2014) indicate that the system has undergone field testing and an acceptability study. A further evaluation of the system was performed by the University of Michigan (CCJ Staff, 2010), which suggests that 38% of drivers indicate that the system has prevented a crash, and that 83% of drivers prefer a truck with the system built in.

In their introduction Kerick et al. (2013) indicate that lane departure systems are effective and may be able to prevent large numbers of crashes, but may also suffer from relatively frequent false alarms (a 14% rate is mentioned). It is also uncertain whether the devices measure fatigue or inattention, or the consequences of fatigue and distraction, and they may alert the driver at a relatively late stage. For the general class of performance monitoring systems, with Safetrak as an example, NHVR (2019) suggests that there is limited validation evidence that the systems detect fatigue or distraction.

A Google Scholar search for the combination of 'Safetrak' and 'lane' (there are other systems that are called 'Safetrak', unrelated to driving) yields several mentions of the system in various papers (Bishop, 2000; Čolić, Marques & Furht, 2014; Jeevagan et al., 2014; Lance et al., 2013), but no articles evaluating the system.

Validity

There appear to be a few system evaluations, mostly focusing on crash prevention (Dawson et al., 2014; Kerick et al., 2013). These indicate that the system is likely to serve this purpose. Less clear is whether the system can be used to detect fatigue or distraction, or instead detects the consequences of fatigue and distraction (e.g., lane departures).

Intrusiveness

No images of the system were found, but it is understood that it uses a forward-facing camera installed inside the cabin. There are some suggestions that the system may need to be integrated into the vehicle. The device is unlikely to interfere with driving.

Availability

The website (www.takata.com), listed on Wikipedia, cannot be reached. A Google search does not yield a link to the website. It is therefore doubtful that the system is still available for purchase.

Robustness

The system will only work for roads that have clear markings. It is unclear whether the system is robust against adverse weather conditions, such as heavy rain or fog.

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Acceptability

Generally, performance-based systems are more acceptable, because they do not involve a camera facing the driver. The study by CCJ Staff (2010) suggests that 83% of truck drivers would like to use the system.

Sustainability

As the availability of the system is doubtful, the same is true for sustainability.

Cost

The cost of the system is unclear. It is currently not possible to contact the supplier for an estimate.

Compatibility

The system appears to be integrated into the vehicle, but also requires a forward-facing camera, which may interfere with other devices needing a similar position inside the vehicle.

3.4.2 Driver monitoring

Table 3.5 provides an overview of computer vision systems that monitor the driver. The main distinction appears to be cost (devices of around $200, and devices of around $800) and, related, flexibility (the lower cost systems are out-of-the-box systems). To which extent the more expensive systems outperform the lower cost systems will need to be established in a field study, as information about performance is highly limited. Within the more expensive systems category, there are systems that seem to be at a further stage of development and testing (Guardian, Eyesight) than others.

Table 3.5. Scores of computer vision systems that use a camera facing the driver

Device	Validity	Intrusiveness	Availability	Robustness	Acceptability	Sustainability	Cost	Compatibility
Stonkam	+/−	+/−	+	+	+/−	+/−	+	+/−
MR688	+/−	+/−	+/−	+	−	+	+	+/−
TS DFM	−	+/−	+	+	+/−	+	+/−	+/−
Abto	−	+/−	−	−	+/−	+/−	NA	+/−
Delphi	+	−	−	+	+/−	−	NA	+/−
Guardvant	+/−	−	+	+	−	+/−	NA	+/−
Eyesight	+/−	−	++	+	+	++	−	+/−
F16 System	+/−	+/−	+/−	−	+/−	−	++	+/−
Guardian	+	+/−	++	+	−	++	−	+/−
Soteria	+/−	+/−	−	−	−	−	NA	+/−
SmartTrans	−	−	−	−	+/−	−	NA	+/−
HxGN Mine Protect	−	+/−	+/−	+	−	+/−	NA	+/−
Toucango	−	+/−	+	+/−	+/−	+/−	−	+/−

3.4.2.1 Stonkam

The Stonkam device is shown in *Figure 3.11*. It is a small unit to be placed on the dashboard, containing an infrared camera facing the driver. Images are analysed for fatigue, phone use, looking away (distraction) and smoking. The company reports a 95% accurate detection of these activities, with somewhat worse performance if the driver wears glasses, and better performance during night-time than daytime. Images are analysed inside the device. When an event is detected, a 20 seconds video of that event is stored and an auditory warning signal given (a voice message). The settings of the device can be adjusted using an interface running on Android devices using WIFI. The device is low-cost: When deployed across a largish fleet, it will be in the order of 200 US Dollars per unit.

Figure 3.11. Images of the Stonkam device
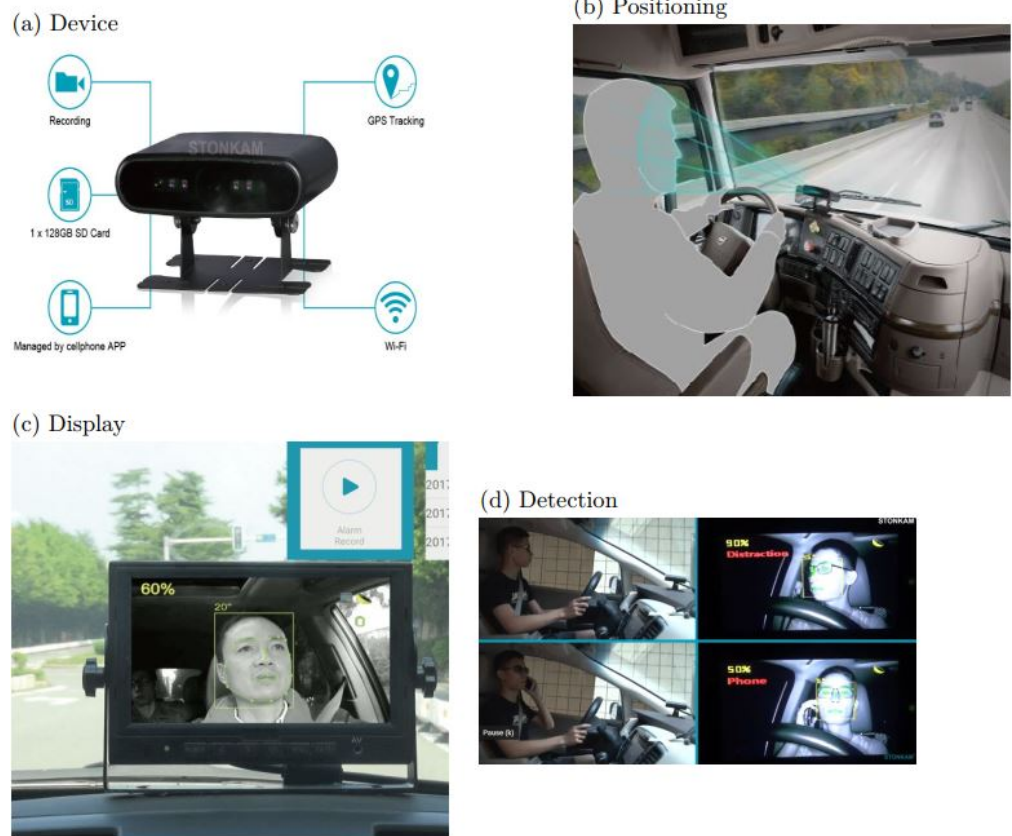
Validity

There do not seem to be independent validations of the system. The supplier indicates the system works at around 95% accuracy.

Intrusiveness

A small unit needs to be fitted on the dashboard (*Figure 3.11b*). The warning messages are provided by a friendly voice, which on the one hand avoids the system becoming intrusive, but may, on the other hand, not be loud enough to wake up a driver.

Availability

The system can be ordered through the Stonkam website. Their support department is responding to information requests.

Robustness

The device is said to work better during night-time than daytime and better when the driver does not wear glasses.

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Acceptability

The device records short videos (20 seconds) of detected events, but these are stored locally. Drivers therefore have control over the device inside the vehicle, which increases the acceptability of the device. The device produces warning messages that may be acceptable to listen to even for long shifts.

Sustainability

It is unclear how long the device will be on the market and how long each unit will run before it needs replacing. The company responds to information requests, which is a sign that the system will be around for some time.

Cost

The device is around 200 US Dollars per unit if bought for a largish fleet.

Compatibility

The device will occupy some space on the dashboard and may therefore be in the way of other devices that need to be placed there.

3.4.2.2 MR688 Driver Fatigue Monitor

The nature of the MR688 Driver Fatigue Monitor device seems to have changed over the years. Dawson et al. (2014) list the driver fatigue alarm as one of the systems using head nodding to detect driver fatigues. A Google search did not return a website for this device. Instead, a computer vision device called Driver Fatigue Monitor MR688 was found (www.care-driver.com).

The system is shown in *Figure 3.12*. Information from the website indicates that it uses an infrared camera and an infra-red light emitter, both pointed at the driver. The images are analysed for signs of fatigue and distraction, for which it seems to use pupil information (called 'mesh membrane pupil detection technology'). This measure may be slightly different from the PERCLOS measure that Kerick et al. (2013) say the device uses.

Figure 3.12. Images of the Driver Fatigue Monitor MR688
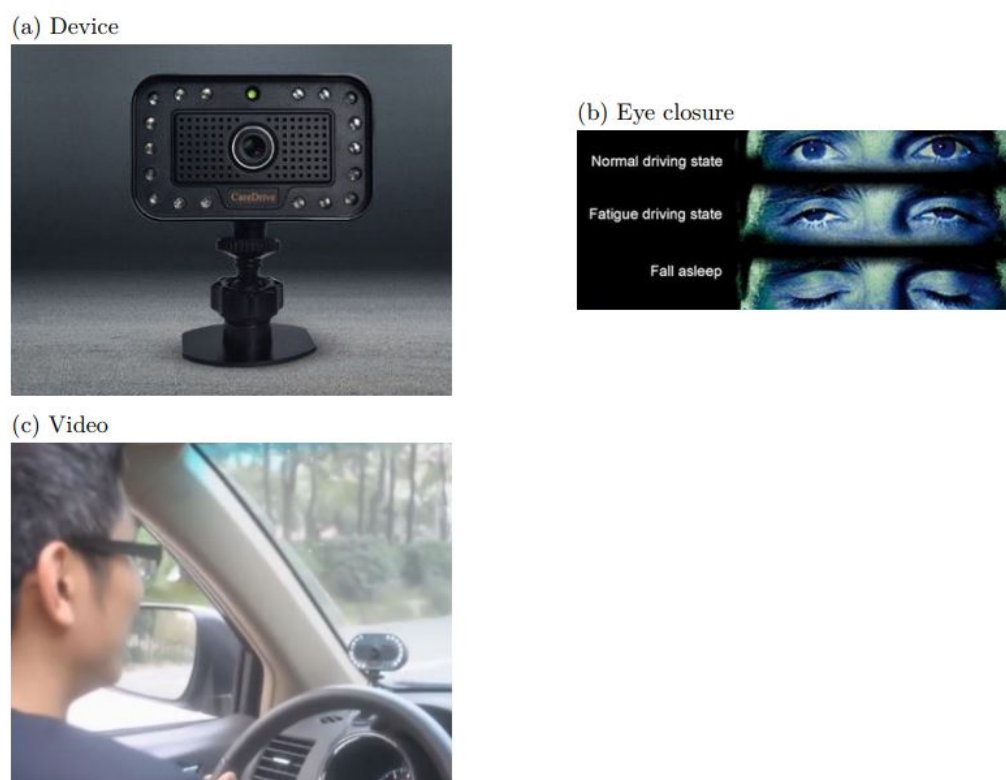
The system is said to work with glasses and sunglasses, for different skin colours and under different weather conditions. When fatigue is detected, the driver is warned with a sound and a message ('keep your eyes on the road'). There is also an option to use seat vibration.

Distraction events that are said to be detected are talking to passengers, bowing one's head, gazing around or spending a considerable amount of time operating audio and navigation systems. The device also offers the option to send the detected event images to the fleet manager. The system can be found on amazon.com (currently not available) and 49riveab.com for around $200. A video on YouTube shows the device in action (Care-drive, 2014): See The video on www.stonkam.com/products/Driver-Fatigue-Monitoring-System-AD-A11.html

Validity
No information about validity of the device was found. The video on YouTube (Care-drive, 2014) suggests that the device responds fairly quickly when the driver looks down or closes the eyes.

Intrusiveness
The device is a small camera placed on the dashboard and it does not seem to be in the way for looking out of the window.

Availability
The device can be ordered from Alibaba.com. There is also a website with contact details (www.care-drive.com).

Robustness
The device is said to work with glasses, sunglasses, different skin colours, and under different weather conditions.

Acceptability
Looking at the video (Care-drive, 2014), the device may get on drivers' nerves if it responds as often as in the video, but the frequency of responses may also be the result of the driver in the video trying to provoke a response from the device.

Sustainability
Besides being available from Alibaba.com, the supplier also has a website. Whether the device will be around for extended periods of time is unclear, but in the short-term it seems the device will be available. It is unclear whether the device requires maintenance or battery charging.

Cost
The device is estimated to cost around $200 (Alibaba.com).

Compatibility
The device emits infra-red light, which may interfere with other devices that rely on infra-red light emissions. The small camera may be in the way of other devices inside the cabin.

3.4.2.3 TS Driver Fatigue Monitor (DFM)
The TS driver fatigue monitor (see *Figure 3.13*) is available from www.transportsupport.co.uk for around $350 (Mabry et al., 2019). It uses a small camera facing the driver and infrared light emitters, ensuring operation at night. The system documentation on the website indicates that it detects the extent to which the driver's eyes are closed (PERCLOS).

The device is said to work for different skin and eye colours, with contact lenses and (after adjustment) with glasses. It detects whether drivers close their eyes, or look around extensively, and the manual therefore warns that too many false alarms may be given if driving involves such extensive looking around.

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There are several warning systems: A high-pitched tone sounds when the system loses sight of the eyes for a short period, a voice alert saying 'keep your eyes on the road' when sight of the eye is not restored within a given amount of time, and a siren alarm when after these two warnings, the eyes are still not visible to the system. Mabry et al. (2019) list the device as unvalidated. A Google search for the system did not yield any relevant results.

Figure 3.13. Images of the TS driver fatigue monitor

Validity
No validations of the device were found, in line with the conclusion by Mabry et al. (2019), who list the device as 'unvalidated'.

Intrusiveness
The device needs to be installed on the dashboard. It produces a green light when the eyes are detected, and may therefore distract from driving. The first warning signal is a high-pitched sound, which may be uncomfortable to drivers.

Availability
The system is available from www.transportsupport.co.uk and no longer in the development stage.

Robustness
The device is said to work for people with different skin colours, wearing contact lenses or glasses, and in daytime and night-time. There are, however, no test results on how well the system works under these conditions.

Acceptability
The system uses a camera and the light indicating that the eyes are detected, may be distracting. The high-pitched tone may be annoying, particularly if the device frequently detects fatigue incorrectly. The device does not send information to fleet management and only operates locally.

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There are similar systems on the market, which do use an indicator light and use a voice as the first warning, which may therefore be preferred by drivers.

Sustainability

This system has its own website, in contrast to similar systems, which are often sold via more generic forums such as amazon.com and 51riveab.com. This makes it more likely that the system will be around for some time. It is unclear how long the system will function under real-world conditions.

Cost

Mabry et al. (2019) estimate the cost at around $350 per device.

Compatibility

The system uses a camera on the dashboard and infrared light. Whether it will be compatible with other systems depends on whether other devices use infrared light or the space occupied by the system.

3.4.2.4   Abto software

Abto software (www.abtosoftware.com) focuses on computer vision applications, of which one is fatigue detection. The fatigue detection software is said to measure how long the eyes are closed, what percentage of the time the eyes are closed, blinking frequency, percentage of eye closure (PERCLOS), head tilt ratio, tangent of head tilt angle, yawn ratio, mouth aspect ratio (MAR), eye aspect ratio, and inverted eye aspect ratio (*Figure 3.14*). The system could work as a standalone application, or transfer images to the cloud for further processing. In an e-mail, Abto software lets us know the fatigue detection software is still in the prototype phase, and no specific hardware has yet been developed to work with the software. For the same reason, no benchmark testing has been performed yet, and no cost information is yet available.

Figure 3.14. Abto software fatigue detection. Images taken from the video on www.abtosoftware.com
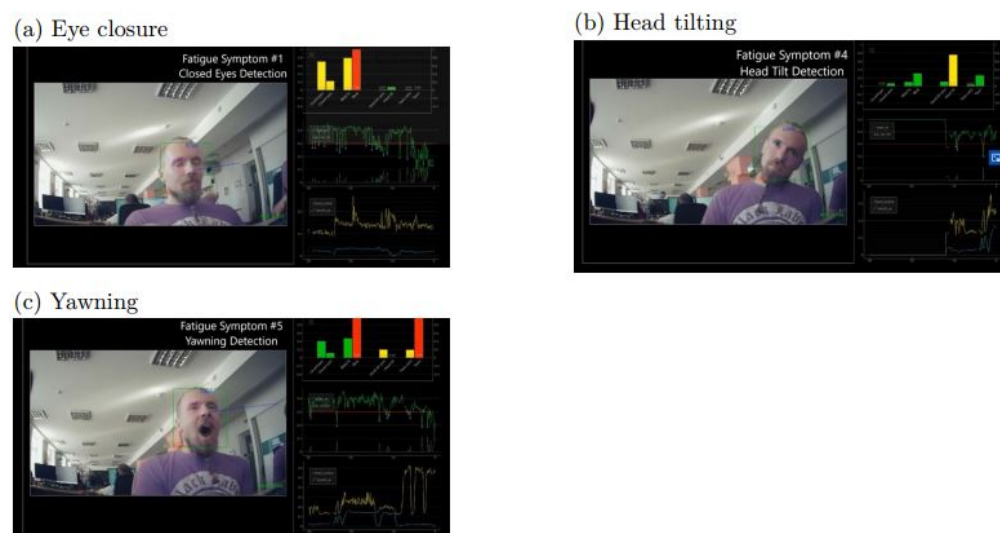
Validity

The system has not yet been evaluated systematically.

Intrusiveness

The system requires a camera facing the driver. Whether this camera interferes with driving will depend on how large it will be an whether it passively records, or whether a light will appear as soon as images are transferred, as is said to happen with other systems.

Availability

Abto is a general computer vision enterprise and fatigue detection appears to be one of its projects. The company lets us know that its fatigue detection software is still in the development stage, and that deployment across a large fleet may need some time to implement.

Robustness

The example video suggests the use of a normal camera, and it is unclear whether the algorithms would also work under night-time conditions with an infrared camera. Neither does the example show whether the system works for a variety of drivers (gender, age, facial hair, glasses).

Acceptability

The system is likely to have the same acceptability issues as other systems that use a camera facing the driver. Drivers may not accept the system (e.g., may block the camera) if the images are uploaded to a server or directly available to fleet management.

Sustainability

As a computer vision enterprise, it is likely that Abto will be around for a while. Whether the fatigue detection project will be continued is less clear. There is quite a bit of market competition, and companies may therefore need to specialise in fatigue detection.

Cost

The system is not yet commercially available and therefore does not yet have a set price.

Compatibility

The device may be in the way of other systems that need to be placed on the dashboard.

3.4.2.5 Delphi Electronics and Safety

The Delphi system was developed by Delphi Electronics and Safety and is described or mentioned in various reviews (Barr et al., 2005; Dawson et al., 2014; Edwards et al., 2007; Golz et al., 2010; NHVR, 2019) and research papers (e.g., Edenborough et al., 2005; 2004). The product is said to consist of two components: the ForeWarn Drowsy Driver Alert system and the ForeWarn Driver Distraction Alert, together combined into a Driver State Monitor (DSM) (Barr et al., 2005). It makes use of a single driver facing camera and two infrared illumination sources.

Figure 3.15.
The Delphi system. Images taken from Edenborough et al. (2005) and Edenborough et al. (2004)
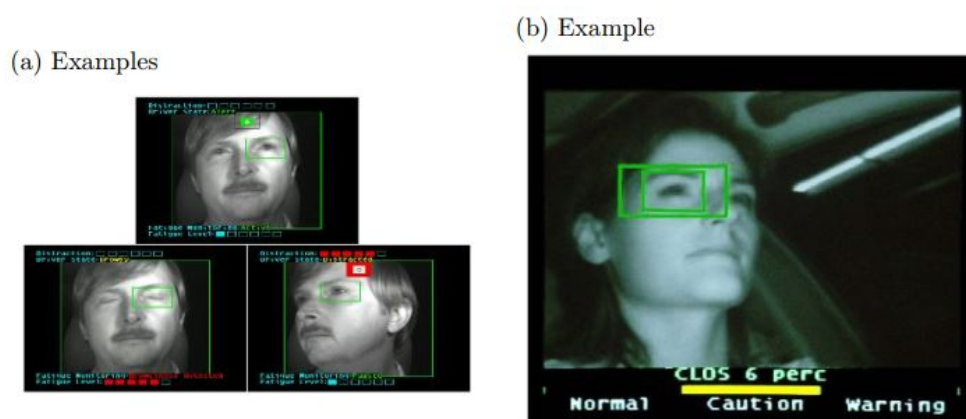
The camera images are analysed using computer vision methods for eyelid closure (AVECLOS, an average PERCLOS measure) and head pose to detect fatigue and distraction (*Figure 3.15*). The device is said to have been installed in a Volvo demonstration vehicle (Barr et al., 2005). Despite a recent review mentioning the system (NHVR, 2019), the device does not seem to be available for purchase. A Google search for 'Delphi' in combination with 'fatigue' led to the research papers and the review papers. A Google search for Delphi Electronics and Safety

suggests that the business has been in financial difficulties. There is a website for Delphi technologies (delphi.com) but a search of the website for fatigue does not result in any hits.

Validity

The research behind the system has been described in two research papers (Edenborough et al., 2005, 2004) and the system has been mentioned in various reviews (Barr et al., 2005; Dawson et al., 2014; Golz et al., 2010; NHVR, 2019). The system does not seem to have been tested on a large scale, or if it has been tested, reports no longer seem to be available.

Intrusiveness

The system makes use of a camera and two infrared emitters, which will need to be placed inside the vehicle. Infrared light is not directly visible, but experience with the Eyelink 1000 eye tracking system applying such infrared emitters suggests that under low lighting conditions, such emitters may not be completely invisible.

Availability

It is unclear whether the system is still available or was available in the past. While a recent review (NHVR, 2019) mentions the system, web searches have not yielded a website to order it from or to ask for more information.

Robustness

The system is said to operate under a wide range of illumination conditions and operating temperatures (Barr et al., 2005). It is unclear whether it also works when the driver wears glasses.

Acceptability

Systems using a camera facing the driver are often considered intrusive. The acceptability will depend on whether such information is processed and immediately deleted, and on the false alarm rate of the system.

Sustainability

Because the system does not seem to be currently available, it is unlikely to provide a sustainable solution.

Cost

It is unclear whether the system has been available for purchase, or at which cost.

Compatibility

The system will interfere with other systems that are susceptible to infrared light.

3.4.2.6   Guardvant

The Guardvant (www.guardvant.com) provided by Hexagon Mining system focuses on the mining industry. It consists of four modules: OpGuard (video analysis of the driver), ProxyGuard (avoiding collisions with workers using video analysis and radar), CasGuard (collision avoidance using GPS), and OpWeb (online tool for fleet management to browse through safety critical events and fleet management).

The first tool, OpGuard, most closely resembles other systems for fatigue detection, but ProxyGuard and CasGuard also serve to mitigate the consequences of fatigue. The exact working of OpGuard is unclear from the description on the website. The video seems to suggest that pupil diameter (PERCLOS) and gaze direction are used to detect fatigue.

Mabry et al. (2019), who use the name 'DriveFit' for the system, suggest PERCLOS using head and facial movements for fatigue detection. The same information is given by Kerick et al. (2013),

who also indicate that optional features are detection of seatbelt use, texting and reading. Feedback to the driver is provided with seat vibration and sounds.

Two peer-reviewed articles refer to the system (Ramya & Kousalya, 2018; Sikander & Anwar, 2018), but both simply describe the main features of the system without indicating how well it works. Mabry et al. (2019) list the system as 'unvalidated', NHVR (2019) simply lists the device, and Kerick et al. (2013) mostly describe its features.
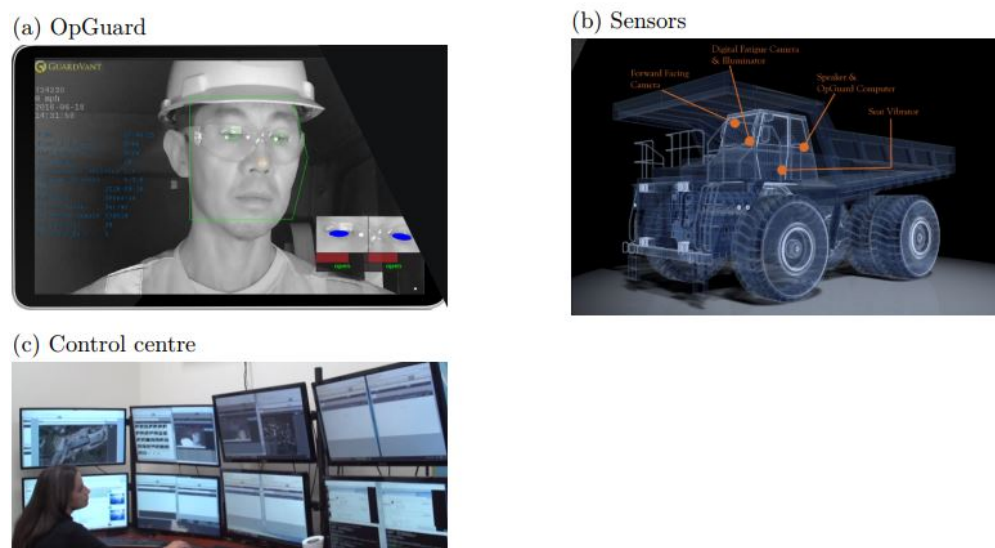
Validity
No studies appear to be available that test the accuracy of detection or acceptability of the system.

Intrusiveness
The system requires the installation of two cameras, radar equipment, a computer, a seat vibration system, and a loudspeaker. An internet connection is needed to transmit images and information to the operator centre. It is unclear how large the different components are and whether they interfere with driving.

Availability
The system is available for purchase through www.guardvant.com. It does not appear to be in the development stage.

Robustness
The system makes use of infrared recordings of the driver (*Figure 3.16a*) and should therefore operate both during the day and at night. Video images suggest that the system works for workers wearing glasses, but Mabry et al. (2019) suggest that glasses may pose a problem.

Acceptability
Workers may not easily accept being video-recorded and the images being sent to fleet management for review.

Sustainability
The system was already described by Kerick et al. (2013), and has therefore been on the market for over half a decade. No information was found on how long the system may be supported for, and whether a subscription fee will be required.

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Cost

Mabry et al. (2019) list the cost as 'currently unknown'.

Compatibility

The system uses infrared light, which may pose a problem to other systems that make use of sensors that pick up infrared light. The system may take up space required for other systems inside the vehicle.

3.4.2.7   HxGN MineProtect Operator Alertness System Light Vehicle

The HxGN MineProtect operator alertness system (hexagonmining.com/solutions/safetyportfolio/operator-alertness/hxgn-mineprotect-operator-alertness-system-light-vehicle) makes use of an infrared camera placed on the dashboard (*Figure 3.17b*). The video on the website suggests that it automatically analyses the images to detect eyelid closure (*Figure 3.17a*), but a further online article suggests that facial feature analysis is performed to detect microsleeps (Hexagon, 2019). The device does not provide real-time feedback. Instead, once fatigue is detected a warning is sent to fleet command (*Figure 3.17c*). The driver is then contacted and the situation is discussed. Videos are stored to allow for reviewing safety critical events. The system may also provide some form of real-time feedback, but information about this option was sparse. A second video (hxgnspotlight.com/tech-highlight-distraction-detection/) suggests that the system also immediately warns the driver with a verbal message ('fatigue alert'). The product is said to work in both light and dark conditions, and through prescription glasses and sunglasses (Hexagon, 2019). The product focuses specifically on the mining industry and allows for fleet management to follow vehicle movements on the site (*Figure 3.17d*). An information request yielded no further information: detailed information was only available to possible commercial partners.

Figure 3.17. The HxGN MineProtect system (images from YouTube).

Validity

No information about validation studies could be found. Very little information could be found about the features and algorithms used by the system, so these cannot be evaluated either.

Intrusiveness

A camera will need to be installed on the dashboard. Whether further equipment is needed (e.g., processing unit, battery equipment, wireless internet connection) is unclear. The system will require some equipment to be placed inside the vehicle.

Availability

The system was launched in 2019 (Hexagon, 2019). While no longer in development, it seems to be a relatively new product.

Robustness

The system is said to work for drivers wearing glasses and sunglasses. It operates during night- and daytime (Hexagon, 2019). Validation studies that indicate how robust the system is under these conditions, have not been found.

Acceptability

Because the system records the driver and sends the recordings to a control centre, the system is likely to raise privacy concerns with the drivers. How these are dealt with, is unclear.

Sustainability

The system has just been introduced, and it is yet unclear whether it would need maintenance, and how long it will still be on the market.

Cost

This information could not be obtained from the website.

Compatibility

The system will take up some space on the dashboard. Whether it requires further equipment to be installed inside the vehicle is unclear. The camera is likely to only interfere with equipment that needs placing at the same location

3.4.2.8 Eyesight

The supplier Eyesight (www.eyesight-tech.com) is dedicated to computer vision products. It provides three main products: (1) Driver sense and Cabin sense, (2) Viewer sense, (3) Device sense. Of these products, the first is aimed at drivers (Driver sense and cabin sense). Driver sense makes use of computer vision and deep learning, and deduces information about eyelid closure, gaze direction, head position and orientation, blink rate and duration and pupil dilation from the driver images. The same system also establishes the driver's presence identity and gender (exactly how this is done, is unclear). The driver's age is also estimated. Cabin sense extends this analysis to passengers in the car, and includes detection of each person's identity, posture and seatbelt use, age and gender, height and body mass, and seat occupancy (*Figure 3.18*). Future releases may also include a detector for objects left behind in the vehicle. Besides detecting phone use and fatigue, the system can also detect whether the driver is smoking, which may be particularly useful in the oil and gas industry.

The system is integrated in the vehicle and makes use of an infrared camera to ensure functionality under different lighting conditions. In future releases, a second forward camera that detects lane departures may be installed. Recordings are processed real-time, meaning no information is stored or transmitted to the cloud for processing, which may ease privacy concerns. Some information below is based on a Skype conversation with the supplier.

Figure 3.18.

The Eyesight system

(a) Driver sense

(b) Cabin sense

(c) Smoking detection

(d) Mobile phone use

(e) Sleep
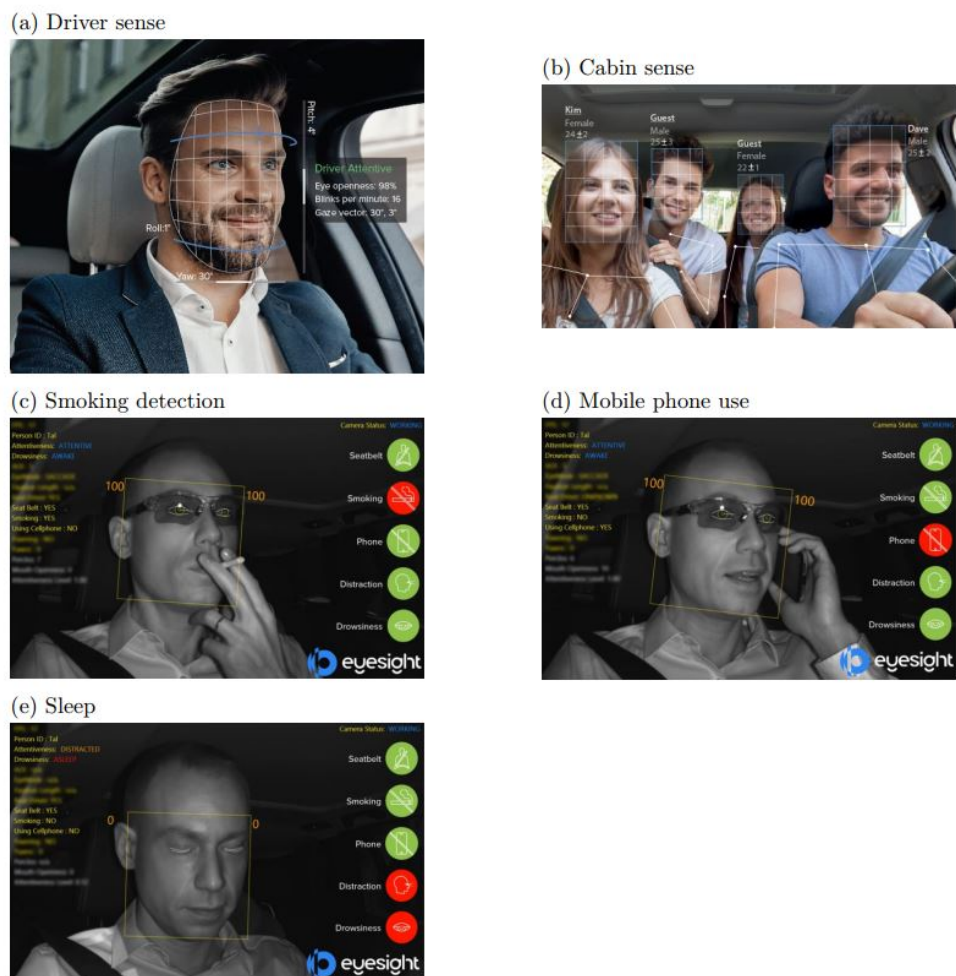
Validity

The videos provided suggest that the system detects fatigue and distraction instantly and accurately. System tests have been performed by Eyesight and external parties, but (for commercial reasons) this information is not publicly available and can only be obtained by commercial partners upon signing a non-disclosure agreement. In a first stage of exploring this system, it would be worth trying to obtain this information.

Intrusiveness

The website does not feature images of the camera itself (only the images recorded). It is therefore unclear how large the camera is, and where in the cabin it should be positioned. It is an integrated system, and can therefore not be removed easily from the vehicle for use elsewhere.

Availability

The system can be ordered on a large scale in a fairly short time-frame (six to twelve months).

Robustness

The system makes use of an infrared camera and should therefore operate under night-time and day-time conditions. The video suggests that the system continues to detect fatigue when the driver puts on glasses.

Acceptability

In contrast to other systems that use a camera facing the driver (e.g., Nauto, Guardian, iDrive AI Cam), all processing is performed real-time and therefore no images need to be stored locally or transferred to the cloud. This is likely to make the system more acceptable.

Sustainability

It can be expected that the system will continue to be available in the foreseeable future.

Cost

Cost information is available upon request. The supplier indicates that the cost aspect is competitive with other similar systems.

Compatibility

The system is likely to be positioned on the dashboard near the driver. It will only interfere with other devices that need to be placed in this location.

3.4.2.9 F16 Fatigue Driving Alarm System

The F16 Fatigue Driving Alarm system is available for around $60 to $70 from Alibaba.com (*Figure 3.19a-c*). The device uses eye-pupil visibility (PERCLOS) to detect fatigue and distraction, derived from the image of the infrared camera and detected using computer vision algorithms (*Figure 3.19d*). The device gives a warning 1-2 seconds after eyelid closure (sound and light). The website indicates that the device is only suitable for private cars, which may be an important restriction in the context of the oil and gas industry. It should work with standard glasses (but possibly not with sunglasses), and under all weather and lighting conditions (bad weather, night).

Amazon.com provides some user reviews. One reviewer mentions that the device reacts well to eyelid closure, and to looking around (with a warning message: 'watch the road'). The same reviewer indicates that the device produces too many warnings during sunrise and sunset, and does not work with sunglasses (as indicated by the supplier). Another reviewer indicates that it works well, but only if mounted correctly. Two reviewers suggest the warning sound should be louder. It is unclear why the system may only be suitable for use in private cars. Otherwise, the relatively positive reviews on Amazon.com and the low cost of the system would make it an interesting option.

Figure 3.19. The F16 device. Images from Alibabi.com

Validity

No independent studies of the system were found. Reviews on Amazon.com were fairly positive.

Intrusiveness

The device needs to be mounted to the window shield. None of the reviewers on Amazon.com indicated that this was a problem for them.

Availability

The device can be ordered from Amazon.com and Alibaba.com. It is unclear how many devices can be ordered at the same time or in total.

Robustness

One reviewer indicates that the devices work less well during sunrise and sunset, and when wearing sunglasses (which the supplier also indicates).

Acceptability

The device does not seem to store data, and only produces warning signals. Users can easily disable the device, and for these reasons it seems to be accepted by the reviewers on Amazon.com.

Sustainability

It is unclear how long the device will be available. No supplier website could be found.

Cost

The device is low-cost ($60 to $70).

Compatibility

The device makes use of an infrared camera, so it will be influenced by devices emitting infrared light. It may interfere with other devices that need to be placed in similar positions.

3.4.2.10 Guardian – Seeing Machines Systems

Figure 3.20 shows the Guardian system. It consists of an infrared camera facing the driver (*Figure 3.20a*). The system analyses the infrared image of the face for gaze and head direction (*Figure 3.20b*). A video on the supplier's website (seeingmachines.com) indicates that bus drivers were reluctant to use the system at first, but that after having been explained the use of the system, they were willing to adopt it. Recently, UK's largest bus operator (National Express) indicated the intention to install the Guardian system in 700 of its buses (Bloomberg, 2019). Besides using computer vision algorithms, the website does not make clear how the system exactly works. It is also not entirely clear when the system came onto the market. For example, Barr et al. (2005) and Dawson et al. (2014) report on the system, but the system's website suggests a 2018 start. The system is sometimes referred to as Seeing Machines (the supplier) and as Guardian (the device). It is possible that the system has seen a few changes and developments over the years.

Seeing Machines also appear to be offering an ADAS system (howentech.com), with features such as a forward collision warning, lane departure warning and headway monitoring warning system, but information about this system appears to be limited to the howentech.com website.

Figure 3.20.
Guardian system from
Seeing Machines

Validity

The device's website (seeingmachines.com) provides several case studies, describing businesses that have used (and valued) the system. Detailed information, such as accuracy of the system, false positive rates, or robustness under different conditions, is not provided. The video suggests the system may be able to detect eye closure, but again without details about accuracy. It is also unclear how the system responds when drivers look around, which may be required for driving, or when there are signs of distraction. The video mentions that around 90% of fatigue events are detected, but does not indicate how such events are measured and under which conditions this performance is achieved.

Evidence from peer-reviewed literature seems to be mixed. Dawson et al. (2014) refer to evidence from an industry report and scores the system as having 'weak evidence' in independent validation and laboratory studies. Barr et al. (2005) indicate that the device has been installed in several driving simulators (including the National Advanced Driving Simulator at the University of Iowa and at the University of Minnesota), and that it has been used in test track experiments at NHTSA's Vehicle Research Test Center. Barr et al. (2005) also indicate that the single-camera system has been installed on a Volvo Safety Truck demonstration vehicle. Mabry et al. (2019) refer to the study by Lenné & Fitzharris (2016) who found a significant reduction of fatigue related events when the device had been installed. The device also seems to have been used in the study by Fitzharris et al. (2017) to show a stronger reduction in fatigue events in the case of feedback to fleet management than with feedback to the driver alone.

Intrusiveness

The system consists of a small camera unit positioned on the console in front of the driver. As such, the system is not intrusive in a physical sense unless other objects need to be placed at that position. Installation of some equipment is needed. The system is not expected to interfere with driving.

Availability

From the news section of the website, it appears the system has been available since 2018, even though reviews from 2005 (Barr et al., 2005) and 2014 (Dawson et al., 2014) already mention the system. These reviews could, however, describe a predecessor. The website lists seven case studies of businesses having tested the system. Guardian therefore seems to be a more established system and is definitely no longer in a stage of development. The news log ends in 2018, but the website is dated 2019, suggesting continued availability of the system.

Robustness

The video available on the company's website suggests that the driver can wear glasses or a cap without impairing the system. It also suggests that, because an infrared camera is used, the system will also work at night-time. Barr et al. (2005) suggest that the device works in bright light and at night-time, with glasses and when the eyes cannot be detected, and at different distances between the camera and the driver. It may, however, well be that the device has seen some ongoing development since the publication of Barr et al.'s review.

Acceptability

A video on the website discusses acceptability at length, because a camera system that is facing the driver can be a major concern to workers. The video suggests that only 3 to 5 seconds of data are stored at any moment, and that the video recordings are only used to monitor head position and gaze direction. There is, however, a mention that when an event happens, video footage may be made available to the employer. This may still be of sufficient concern to workers, and it may therefore be important that this feature can be disabled.

Sustainability

The system seems to have passed the development stage. As such, the camera appears to be robust, and there is no reason to expect that the system would need to be updated often.

Cost

This information has to be requested (Mabry et al., 2019) and is likely to depend on the number of vehicles that will be equipped with the system. Personal communication with vendors of another, similar system suggests that Guardian may be one of the more expensive systems on the market. Information from one of the commissioners of this report confirms this suggestion.

Compatibility

The system is not expected to interfere with other systems in the cabin, unless they need to be positioned directly in front of the driver.

3.4.2.11 Soteria

The Soteria system (soteriasafedriving.com) makes use of a small camera (taking images every 15 seconds) and GPS sensor (attached to the upper right corner of the front window, see *Figure 3.21a*), connected to a Raspberry Pi processing unit using deep neural networks to detect whether a driver is distracted (*Figure 3.21b*). The project started in the wake of a competition initiated by an insurance company (State Farm) on the data science website Kaggle (www.kaggle.com; Kaggle, 2016), which asked contestants to implement an algorithm that could classify 102,150 images of distracted drivers into one of nine categories.

The system achieved an accuracy of 56% (the related chance level is unclear; safe driving images seem to be over-represented, which will form the majority class), and was mostly struggling to differentiate 'between safe driving', 'talking to a passenger', and 'hair and makeup'. The images and GPS data are processed on an Amazon Web Service, and stored in AWS Simple Storage Service. The system is being prepared for commercial deployment. It is one of the few systems that specifically targets distraction.

Figure 3.21. Images of the Soteria system (from soteriasafedriving.com)
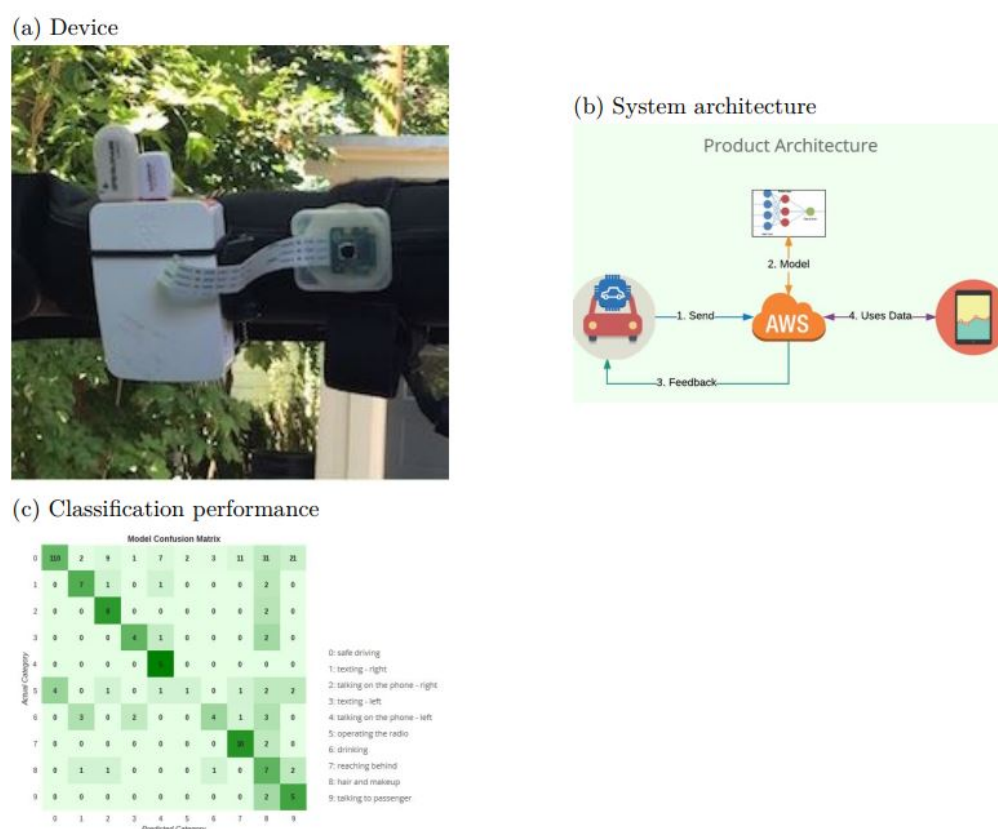
Validity

The only information about the performance of the device appears to be available through the website (soteriasafedriving.com). The confusion matrix shown on the website suggests that safe driving was often misclassified as distracted driving (false alarms). The website also suggests that such false alarms are avoided by setting a threshold with a probability of distraction of 95% before a warning is given. While reducing the false alarm rate, this will also increase the number of distraction events that are missed.

Intrusiveness

The device consists of a small unit placed in the corner of the front window. As such it is unlikely to strongly interfere with driving.

Availability

The device is not yet commercially available.

Robustness

Robustness is a limitation for the device, as acknowledged on the website. The training-set used for the current version has a limited range of lighting conditions, camera angle, vehicle type, and driver characteristics. Robustness is likely to improve while more data are being collected.

Acceptability

Acceptability may also be an issue, as data are sent to a commercial cloud service (Amazon) for processing and storage. While the website indicates not to make these data available to third parties, storage security will depend on the web service and how careful data storage is handled. The high number of cases of normal driving that are classified as distracted driving, may also be an issue.

Sustainability

The device is not yet available, and there is no information on future availability either

Cost

The device is not currently for sale, so no price has been set. The cost of the equipment can be expected to be low, but the cost will likely be determined mostly by the web service used and development costs.

Compatibility

The device can be placed in the corner of the window and is therefore not likely to interfere with other systems such as navigation or communication devices.

3.4.2.12   **SmartTrans**

SmartTrans (smarttrans.us) is developing a system that combines three sources of information on driver fatigue: (1) results from a questionnaire on driver fatigue delivered with a phone app, (2) a camera that monitors the driver, (3) sensors that register information from inside the cabin (*Figure 3.22*). With these three sources of information, the system aims to predict when fatigue related incidents are about to occur, rather than to intervene when they actually occur (SmartNotify, 2019). The website indicates that the product is still in private beta, which is confirmed by the review by Mabry et al. (2019). Mabry et al. (2019) indicate that the sensors inside the vehicle may measure light, air quality, noise and temperature. The camera may detect gaze direction and heart rate. The video suggests the system uses voice messages to warn the driver.

Figure 3.22. SmartTrans system. Images taken from various sources

(a) Sensor

(b) Video analysis

(c) Phone App
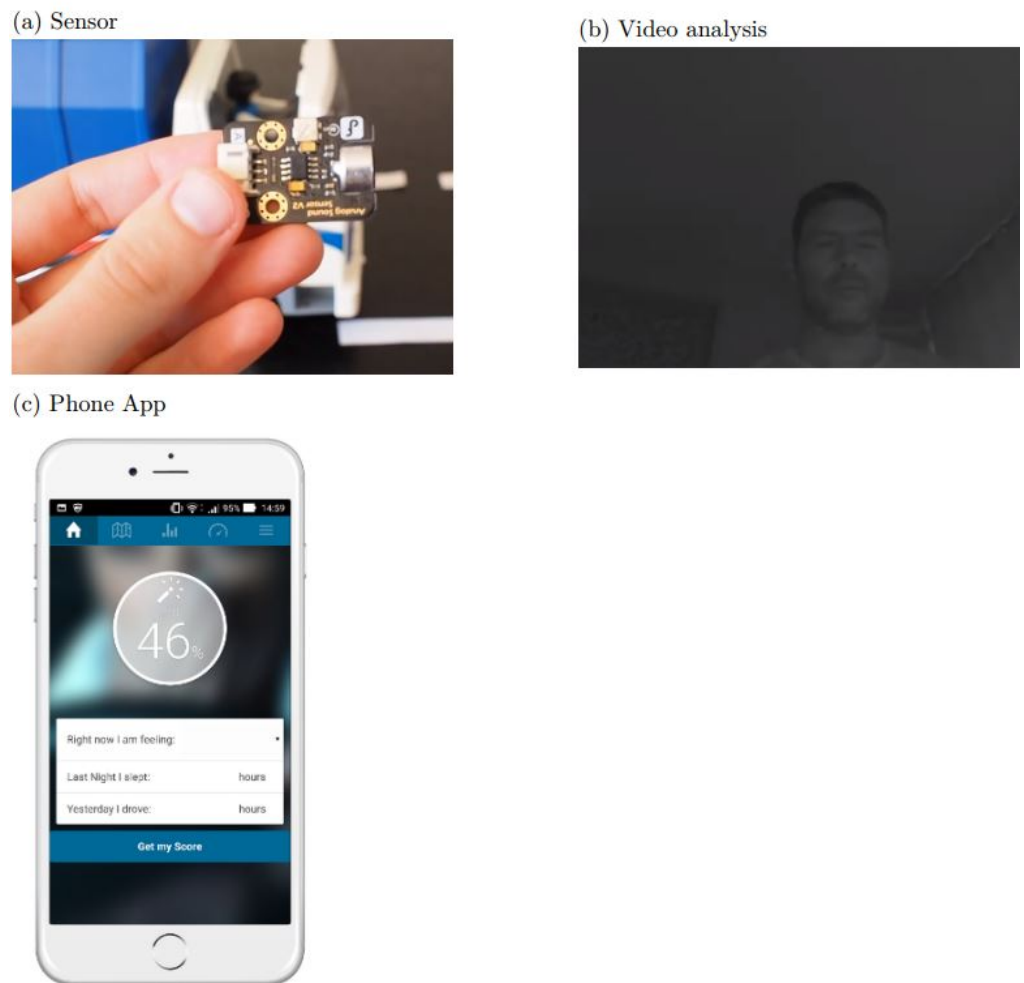
Validity
The system is still in beta mode, and no evaluations are yet available. The concept of combining multiple sources of information to improve prediction and detection is supported by various reviews (Dawson et al., 2014; Kerick et al., 2013).

Intrusiveness
The system requires the installation of sensors, a camera and an app on the driver's phone. It is not expected to interfere with driving.

Availability
The system is still in beta and therefore not yet available.

Robustness
It is unclear how well the system works under various conditions.

Acceptability
Acceptability will depend on the false alarm rate and whether information is reserved to the driver, or will be shared with fleet management.

Sustainability
The system is not yet available.

Cost
This is information is not yet available.

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Compatibility

The system will occupy some space in the cabin that may be needed by other devices.

3.4.2.13 Toucango

Toucango (toucango.com) is a device consisting of a tablet and a camera facing the driver (*Figure 3.23*). The device analyses features of the driver's face to detect drowsiness or distraction, and produces a warning tone and visual signals in case of a detected event. Exactly what measures (e.g., eyelid closure, blink frequency, gaze direction) the device uses, does not become clear from the documentation. Information from the supplier suggests that the cost of the device would be in the same order as the more expensive computer vision systems.

Figure 3.23. Images of the Toucango system (from the vendor's YouTube channel)

(a) System positioning

(b) Camera view
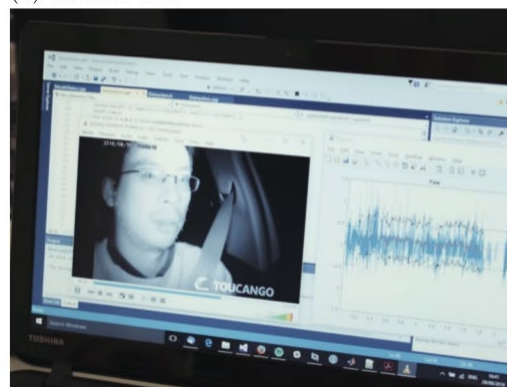
Validity

The video on the vender's YouTube channel suggests that the device has been tested in buses (Eurolines) and vans, but, in an internet search, no independent test results could be found.

Intrusiveness

The device consists of a small tablet and a camera. Only the camera needs to be near the driver, and the system is therefore not expected to interfere with driving.

Availability

The vendor responds to e-mails and the system is available for purchase.

Robustness

No information could be found on how well the device works under different weather conditions, at different viewing distances between the device and the driver, or when the driver is wearing glasses.

Acceptability

The video on the YouTube channel suggests that the device can also be used for fleet management and that information about events is being sent to a central operator. This may raise acceptability issues with drivers, who may not want their data being shared with their employer.

Sustainability

The device is currently available, but future availability is unclear.

Cost

The cost will be similar to that of the more expensive computer vision systems.

Compatibility

The camera is of similar size to that of other systems. Therefore, it is not expected to interfere with other systems.

3.4.3 Monitoring road and driver

Table 3.6 provides an overview of computer vision systems that monitor both the driver and the road. The information that could be obtained about the systems did not suggest one system to be clearly outperforming the other systems. Two systems may be preferred for different reasons. Nauto has been tested by Uber drivers, who have shared their experiences with the system and the approximate cost of the system, providing independent evaluation of the system. Acceptability, however, seems to be an issue for Nauto, but cost is low. A more expensive, but also more flexible system is Streamax, which allows sharing of the images with fleet management to be disabled. In cost, the system is similar to other systems that only use a single camera, but the system does not appear to have been independently tested.

Table 3.6. Scores of computer vision systems that use both a forward camera and a camera facing the driver

Device	Validity	Intrusiveness	Availability	Robustness	Acceptability	Sustainability	Cost	Compatibility
Idrive	+	+/–	+/–	+/–	+/–	+/–	NA	+/–
Exeros	–	+/–	+	+/–	–	+/–	NA	+/–
Zendu Cam	–	–	+/–	–	–	+/–	NA	+/–
Nauto	+	–	++	+	–	++	+	+/–
Streamax	+/–	+	++	+	+	+	+/–	+/–

3.4.3.1 Idrive

The company Idrive Global (idriveglobal.com) provides four services: Reports and analytics, driver monitoring technology, fleet management and AI technology. Their device for fatigue and distraction monitoring is the AI cam, consisting of a smartphone size device with forward and inward (road and driver) facing cameras (*Figure 3.24a*). The cameras record in HD quality and make use of Infrared LED for low-light recording and night vision.

The device is said to make use of 11 billion miles of video data under a broad range of driving conditions using deep learning to extract relevant features from the images for fatigue and distraction detection. Processing is said to be done inside the device, allowing for video sections to be stored containing images from just before and after critical events. There is also an option to record continuously. The device is reported to be able to recognise the driver (*Figure 3.24b*), provide unsafe distance warnings, detect drowsy driving, detect seatbelt use, predict road crashes, and detect distracted driving (adjusting radio, reaching or looking back, smoking, eating and drinking, talking on the phone, texting, *Figure 3.24c*). Video footage can be transferred using WIFI, Bluetooth, or cellular signals. The device was brought to market in November 2019 and aims to add further AI features in the first quarter of 2020 (Business Wire, 2019).

Figure 3.24.

The Idrive AI cam system

(a) Device

(b) Camera view

(c) Events detected

Validity

Some numbers are reported on the website (idriveglobal.com) indicating an over 90% accurate detection of relevant events. No information is available about the types of errors in the remaining 10%. If these mostly include false alarms, this will likely make drivers disable the system. Information on the website (idriveglobal.com) also suggests that a trial with taxi drivers saw a 58% reduction in drowsy driving after use of the system. How the number for distracted driving needs to be interpreted (not a percentage) is less clear. It is unclear what algorithms the system uses to detect events, which makes it difficult to evaluate the results.

Intrusiveness

The system requires the installation of a small unit on the dashboard. It is unclear whether this unit can easily be moved to different vehicles. Driving is unlikely to be affected by the device.

Availability

The product has just been brought to market. New features are expected in the beginning of 2020 (Business Wire, 2019). The device is said to be made available on a first-come-first-served basis (Business Wire, 2019).

Robustness

The system operates with HD infrared cameras and should therefore function under day- and night-time conditions. It is unclear how well the algorithm works under adverse weather conditions (e.g., heavy rain, fog) or still achieves the 90% + accuracy when the driver is wearing glasses, a hat, or changes facial expression.

Acceptability

Because the camera faces the driver and recordings can be transmitted over the web, drivers may have issues with the system, because of privacy concerns. It is unclear how such concerns are mitigated.

Sustainability

The device has just been brought to market. The company providing the device, however, has been in business for over 10 years, which makes it more likely that the product will be continued in the foreseeable future.

Cost

The website does not offer an indication of cost. An e-mail inquiry did not yield any results.

Compatibility

The system will interfere with other devices that require being placed on the dashboard. It may also require connectivity in terms of WIFI, Bluetooth, or cellular connections.

3.4.3.2   Exeros facial recognition and ADAS

Exeros technologies (www.exerostechnologies.com) offers two technologies: A facial recognition system and a forward-facing camera (the ADAS part). It is unclear whether the two systems can be combined to improve fatigue and distraction detection. By analysing the infrared images, the system can detect fatigue (eyelid closure, *Figure 3.25a*), distraction (looking elsewhere, *Figure 3.25b*), phone use (*Figure 3.25c*) and smoking. The forward-facing camera can detect the distance to the vehicle ahead and unexpected lane departures (*Figure 3.25d*).

Figure 3.25. Exeros facial recognition and ADAS system. Images retrieved from www.exeros-technologies.com
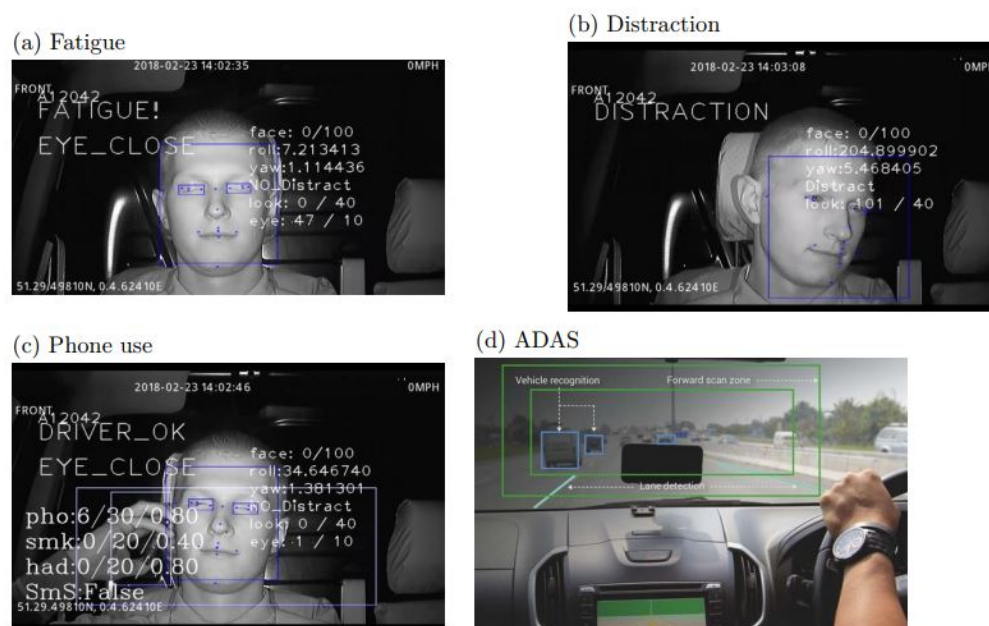
Validity

Results that were provided after an e-mail request showed that significant numbers of events (e.g., fatigue, smoking, distraction) are detected.

Intrusiveness

The system will require the installation of cameras facing the road and the driver. Whether other equipment needs to be installed, is unclear. How large the equipment is, and whether the system will interfere with driving is also unclear.

Availability

The website provides the opportunity to receive a quote for a larger number of devices. The supplier responds to e-mail.

Robustness

Documentation provided by e-mail indicates that the system also works when the driver wears glasses, and under night-time driving conditions. It may not work with sunglasses.

Acceptability

The system uses a camera facing the driver. It is understood that the system can process these images locally, without transmitting the images to a central server, which makes the system more acceptable.

Sustainability

The system appears to have been brought to market in 2018 although an earlier version using PERCLOS was already described by Kerick et al. (2013). Whether the system requires maintenance or updates, and how long it will be available, is unclear.

Cost

For a largish fleet, each unit would cost around 650 GBP.

Compatibility

Except for taking up space inside the cabin, the system is not expected to interfere with the operation of other systems.

3.4.3.3 GoFleet Zendu Cam

The Zendu Cam from GoFleet uses two (infrared) cameras: one facing the driver and the other facing the road (*Figure 3.26*). Using facial detection and artificial intelligence software (see video on zenduit.com), the system detects driver distraction (the eyes away from the road for three seconds or more), mobile phone use (one hand on the steering wheel), texting or social media use, drinking, fatigue (slow blinking, head nodding, eyes away from the road). Images from the forward camera, together with GPS information, are sent to the cloud for monitoring by fleet management.

Figure 3.26. Zendu cam from GoFleet. Images from www.gofleet.com
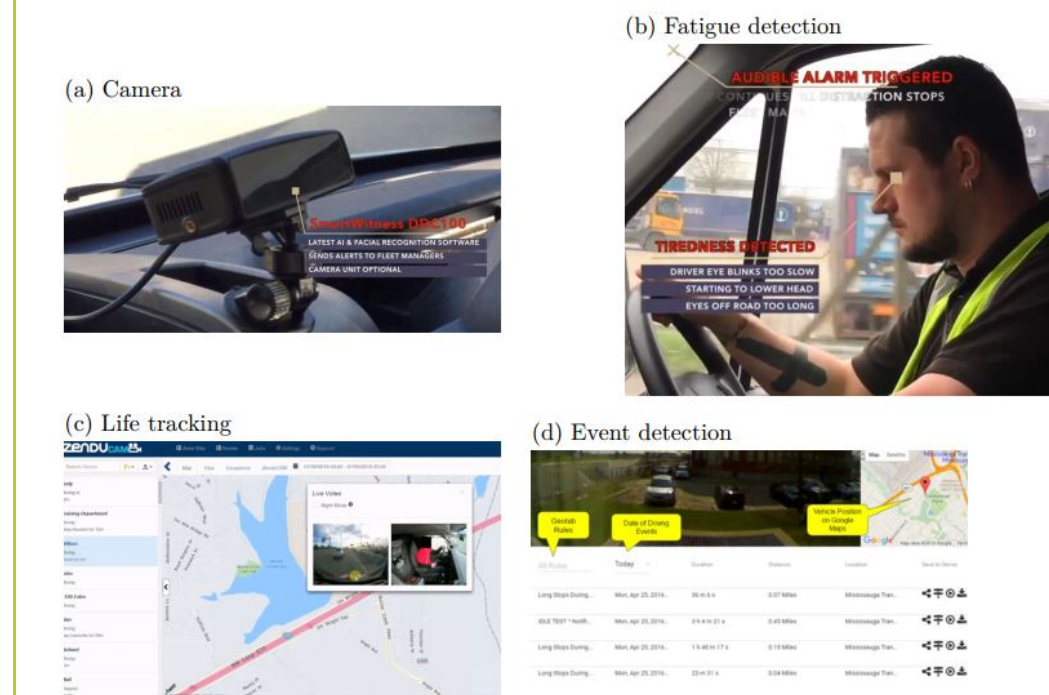
Validity

No information could be found about validation studies.

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Intrusiveness

Two cameras need to be placed inside the vehicle. The data are transmitted to the cloud. It is unclear whether data processing takes place locally or on an external server.

Availability

Although there is little information available about the product on the website, the product appears to be commercially available. A Google search suggests GoFleet has 48 employees and is worth several millions of dollars. Most of its operations seem to be in fleet management.

Robustness

No information could be found about robustness.

Acceptability

Images are uploaded to the cloud, which may be a problem for drivers.

Sustainability

While GoFleet in itself seems to be an established business, the Zendu cam appears to be one of many products offered. As a consequence, long term support may not equal that of other devices using computer vision.

Cost

No information could be obtained about cost.

Compatibility

The device will interfere with other systems that occupy the same space in the cabin, but is otherwise not expected to interfere with other systems.
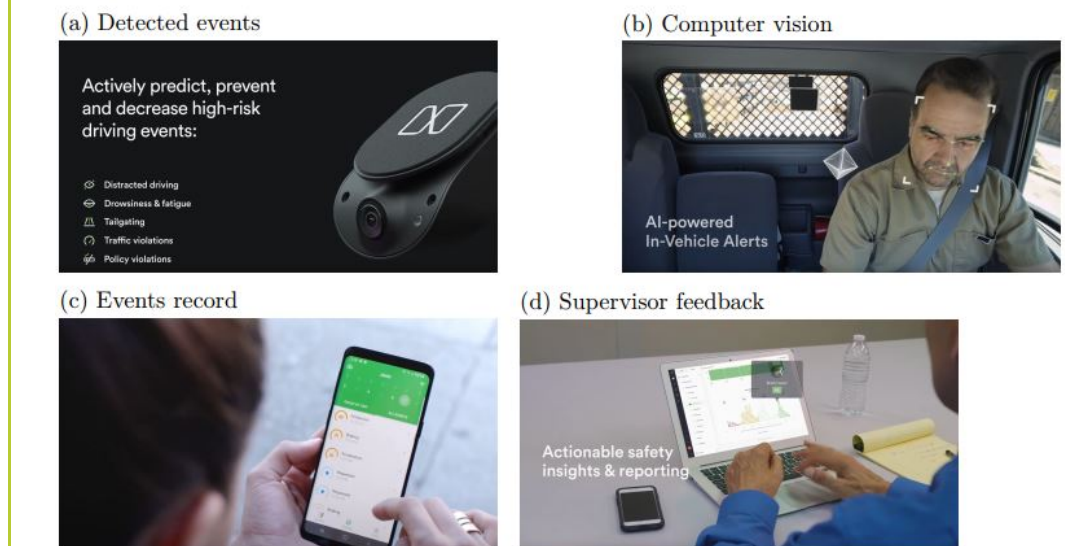
3.4.3.4   Nauto

Figure 3.27 provides images of the Nauto system, which was registered for a patent in 2018 (Levkova et al., 2019). The system is offered to Uber drivers at a cost of around $5 to $10 per month (Conger, 2019). Information on the website suggests it detects distracted driving, drowsiness and fatigue, tailgating, traffic violations and police violations (*Figure 3.27a*), but the main focus of the device appears to be distraction detection.

The system makes use of two cameras (one directed at the road, one at the driver), GPS, and accelerometer data (*Figure 3.27b*; Boada, 2018). It uses deep learning to classify g-force patterns as crashes or non-crash events, using a large database of g-force patterns that match such events, which is expanding while the system is being used by drivers (Lu, 2019). Images from the camera facing the driver are automatically analysed for signs of fatigue and distraction (Lu, 2019).

The system is not only used for online monitoring, but also for driver training (Boada, 2018). This latter aspect is also what raises concerns with drivers. Uber drivers question the privacy of the system (Conger, 2019; Kustoms, 2018; UberPeople.net, 2018). An important reason is that events and corresponding video recordings (*Figure 3.27c*) are stored and transferred for discussion with a coach (*Figure 3.27d*).

(a) Detected events

Actively predict, prevent and decrease high-risk driving events:

- Distracted driving
- Drowsiness & fatigue
- Tailgating
- Traffic violations
- Policy violations

(b) Computer vision

AI-powered In-Vehicle Alerts

(c) Events record

(d) Supervisor feedback

Actionable safety insights & reporting

Validity

No peer-reviewed evidence of the system's effectiveness could be found. Boada (2018) describes results of an eight-month study that showed reductions in distractions and collisions, but no formal report that shows these data could be found. The study showed that four out of five drivers saw improvements in distraction frequency (40% reduction) and duration (43% reduction), distance travelled while distracted (47% reduction) and collisions (81% reductions) due to the system's alerts (Boada, 2018), although it is unclear how exactly the study results were achieved s. The results of Boada's test also seem to focus strongly on distraction detection, and it is unclear how well the system detects fatigue.

The blog on the Nauto website (nauto.com) describes the rationale of the system in substantial detail (e.g., the use of deep learning to detect collisions from g-force patterns, see Alpert, 2019, and Lu, 2019). Case studies on the website report that educating drivers about the system leads to a 70% increase in safety compliance (and 90% in 12 months) and a reduction of 81% in collisions in the first three weeks of using the system. The system is also said to lead to exonerations of wrongful collision claims (nauto.com).

Intrusiveness

The system requires the installation of equipment inside the vehicle. The cameras may distract the drivers, particularly if they become aware that the video recordings may be seen by others.

Availability

The system is currently in use by Uber drivers. The system undergoes continuous updates to improve its performance, but it is no longer in a development stage.

Robustness

Videos recorded by Uber drivers (Kustoms, 2018) suggest that the system detects distraction from mobile phones quite accurately (which may be a problem for Uber drivers, who need to check their phones for new orders). A blog post on the use of deep learning for distraction detection (Alpert, 2019), suggests that the use of deep learning, making use of 150 million AI-processed video miles, improves distraction detection under real-world conditions (variable eye shapes, lighting conditions, accessories, occlusions), compared to traditional algorithms. Exact data on this comparison, however, do not seem to be available. How well fatigue detection works under real-world conditions is less clear.

Acceptability

Drivers complain about the system producing too many warnings (Kustoms, 2018). The transmission of the video images to the cloud also raises privacy issues (Conger, 2019). These observations suggest that drivers may struggle to accept the system. Driver education, including examples of how the system may be used to exonerate drivers in false collision claims, may improve the situation, but for taxi drivers in particular, customers may be put off by the images not being erased immediately after they have been analysed.

Sustainability

The system was deployed in 2017 (Alpert, 2019), and is now in use in many Uber taxis (Conger, 2019). Privacy concerns may be an issue for the system's future, but this may be solved by providing warning-only options to users (although, at the moment, the company seems keen to collect video data to improve the system).

Cost

The system costs around $5 to $10 per month (a subscription fee; Conger, 2019). Whether this is the cost that is charged to all possible customers is unclear, and it may vary with the number of licenses purchased.

Compatibility

The system needs to be installed inside the dashboard and may take up space that drivers may want to use for other purposes (Kustoms, 2018). It also requires the installation of two cameras that may take up space.

3.4.3.5 Streamax

The company Streamax (en.streamax.com) is based in China, but operates globally, and has representatives for Europe and the US (working with companies in these countries and Mexico). The company provides a broad range of camera systems, including a system that monitors the road with a forward-facing camera (an ADAS system) and a camera monitoring the driver (the Driver State Monitor). *Figure 3.28* shows the driver state monitor. It uses an infrared camera and analyses the images for positions of the eyes, mouth and face. It also detects the presence of a mobile phone or a cigarette, and hand movements that suggest talking on the phone or smoking. The forward-facing camera can be used to detect lane departures and near-collisions with vehicles ahead or with pedestrians. Fatigue is detected by looking for signs of yawning, eyelid closure, and blinking. Distraction is detected when the eyes are taken off the road for a certain amount of time (can be set flexibly). In case of fatigue and distraction (or disabling of the camera) the system produces a tone, which can be set flexibly.

Information from one of Streamax' representatives indicates that the number of cameras is flexible, and will determine the cost per vehicle. For cars, a forward and driver facing camera will suffice. Trucks may benefit from an extra camera that covers the blind spot. Buses may have additional cameras inside the vehicle to monitor the passengers. Exact numbers would depend on the total order, but for a largish fleet, a single driver monitor per vehicle (e.g., a camera facing the driver only) would be less than the approximate $800 of many systems in this category. A system with many cameras (e.g,. for surveillance in buses) would be more than this amount (around twice or three times).

Information from the same representative indicates that the system has been tried out extensively in buses in China and suggests accuracy rates of around 90 to 98%. While the number of samples on which these numbers were based was available, a split between misses and false positives was not shown. The system would need to be installed inside a vehicle, but this would be possible with a manual, without the need of any engineers on site.

The system sends images to fleet management by default, but intermediate options would be available, such as storing images locally with password protection, or simply providing a warning sign without transmitting or storing images.

(a) Camera

(b) Image analysis

(c) Tablet

Validity
A field study in buses by Streamax suggests an accuracy rate of 90-98%. How this splits in misses and false alarms, or exactly what samples the accuracy was based on, is unclear. No independent literature could be found on the system's performance.

Intrusiveness
The system uses a combination of a one of more cameras, a processing unit, and a small screen for feedback. Only the camera needs to be placed near the driver, but does not have to be in front of the driver. The volume and nature of the warning sounds could be set to be sufficient to wake the driver up, but not to be annoying in case of false positives.

Availability
The system can be ordered in large quantities from the supplier.

Robustness
A YouTube video shows that the system also works when the driver wears sunglasses. This was also confirmed by the representative. Because of the use of an infrared camera, it can also be expected to work in darkness. How robust the system is against other factors is less clear.

Acceptability
For training and legal purposes, the system shares videos with fleet management by default. Not all drivers may accept such sharing. The system can be adjusted in this respect, and can store or process images locally instead, increasing acceptability for drivers.

Sustainability
Streamax has been operating since 2002 and currently employs around 200 workers (with 800 in research and development). This makes it likely that the system will be on the market for a while.

Cost

The cost will depend on the number of devices purchased and the number of cameras and features per vehicle. It has been suggested that for a single camera for a largish fleet cost will be lower than $800 per unit. For many cameras (e.g., inside a bus), the cost may be double or triple this amount.

Compatibility

The camera and unit are small, and are unlikely to cause compatibility issues.

3.5 Activity trackers

Activity trackers make use of accelerometers to infer activities such as sleep, walking and running (Kolla, Mansukhani & Mansukhani, 2016). Users often purchase and wear them to try and improve their lifestyles (Shih et al., 2015). Various commercially available devices, such as FitBit, Jawbone, Lumoback and Pulse have been extensively validated for their ability to measure activities, such as counting steps (Kooiman et al., 2015), energy expenditure (Sasaki et al., 2015) and sleep (De Zambotti, Baker & Colrain, 2015; De Zambotti et al., 2016; Lee et al., 2017), generally showing high accuracy and reliability in many devices. For sleep specifically, devices tend to be accurate at detecting sleep, but less accurate at detecting whether a person is awake (De Zambotti et al., 2016; Lee et al., 2017), suggesting that periods of low activity are more often classified as 'sleep' by such devices.

Fitness and sleep trackers do not seem to be used to directly monitor onset of fatigue or sleep when driving. Instead, they are used to objectively measure sleep quality before driving, to feed into fatigue models, such as SAFTE or CAS (Brown, 2012; Hursh et al., 2004; Mallis et al., 2004), to predict periods when the driver should take a break or a nap.

Table 3.7 compares two activity trackers that combine with a computational model. The table also contains the scores for a fatigue model (CAS) and a body temperature system that does not fit inside any of the other categories. The *Appendix* will describe some sleep trackers that do not combine with a computational model, and will therefore be less beneficial for fatigue management than the two systems that do use a combination. The two activity trackers (Readiband and Cat Smartband) do not seem to differ much. While the systems can help determine when a driver needs to take a break, they will not provide an immediate warning for acute periods of fatigue.

Table 3.7. Scores for systems using activity trackers in combination with a fatigue model, a fatigue model (CAS), and a system that uses temperature monitoring

| Device	Validity	Intrusiveness	Availability	Robustness	Acceptability	Sustainability	Cost	Compatibility
Readiband	+	+/–	++	+/–	+/–	+	+/–	+/–
Cat Smartband	+	+/–	++	+/–	+/–	+	+	+/–
CAS–5	++	+	++	+/–	+/–	++	NA	+
Bodycap	–	–	+	–	–	–	+	+/–

3.5.1 Readiband

The Readiband combines a wristband (*Figure 3.29*) and a computational model to derive sleep state and to predict episodes of fatigue. The model applied is the Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE) model, which has been used by the US Army and the US Air Force (Brown, 2012; Hursh et al., 2004).

The SAFTE model is only commercially available, and has not been independently validated (Dawson, Darwent & Roach, 2017), but a systematic validation of the SAFTE model in combination with the Readiband by the supplier (Russell et al., 2000) on the basis of 50 participants in a sleep clinic suggests sleep state (awake or asleep in bed) is classified with a 93% accuracy compared to the 'gold standard' (polysomnography). The SAFTE algorithm outperformed four other commonly used algorithms in terms of specificity (correctly detecting participants were not asleep). Classification was also consistent between two Readiband devices worn simultaneously with around 95% agreement (Driller, McQuillan & O'Donnell, 2016), which was also confirmed when the devices were worn on different arms of the same participant.

A follow-up study called for more caution, and suggested that Readiband underestimated various measures of sleep quality. It did add, however, that the system was adequate for detecting sleep duration (Dunican et al., 2018).

Figure 3.29.Readiband tracker and software
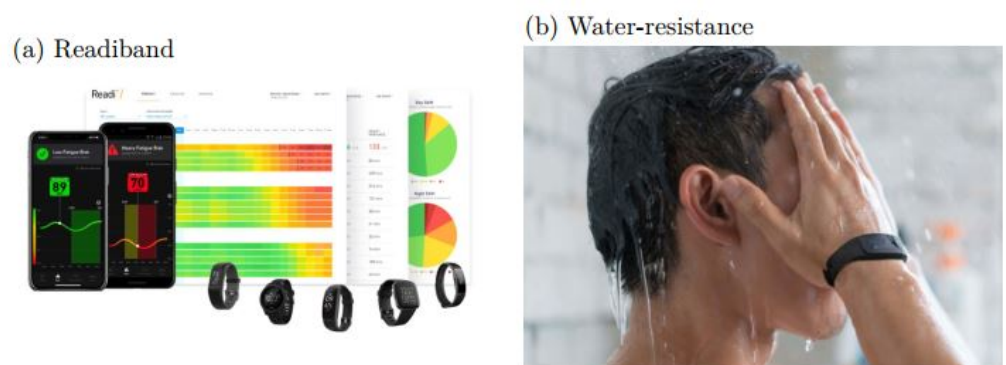
Validity
There is evidence that the device correctly measures whether the user is awake or asleep in bed (Russell et al., 2000) and that the device is adequate for sleep duration (Dunican et al., 2018). The SAFTE model that is used for predictions has proved to accurately predict periods of reduced alertness (Brown, 2012; Hursh et al., 2004). The device may add to the technologically less complex PVT reaction time test (Khitrov et al., 2014) by predicting intervals of fatigue, rather than providing an estimate of fatigue at the time of testing only.

Intrusiveness
The system requires the user to wear a wristband, during and away from work. The device is not expected to interfere with driving.

Availability
The device is available from the supplier's website. The device has been adopted in industry, elite sports and the military.

Robustness
The device makes use of an accelerometer, which should be robust against factors such as heat, dust and impacts. It is also resistant to water (*Figure 3.29b*).

Acceptability

The Readiband and underlying model allow for a fairly fine-grained decision on the worker's readiness-to-work, and may allow workers to start a shift while recommending to end the shift earlier, and may therefore outperform fitness-for-duty tests. Workers may find it problematic to wear the Readiband away from work, because it may provide the employer with information about sleep times and quality, which may vary for various reasons. Acceptability of the device will depend on how well the device's assessments match the subjective levels of fatigue. Workers may need to be informed that subjective sleep levels do not always match objective ones.

Sustainability

The supplier's website (www.fatiguescience.com) lists 13 current users, including the US army and US air-force, the NFL and the NBA. It has support teams that operate from the US, UK and Canada. The website offers replacements at reduced cost. With the research backing up the underlying SAFTE model, it can be expected that the system will be available for the foreseeable future.

Cost

The website lists a cost of USD $695.00 for the "ReadiBand 5 including actigraph hardware and a perpetual license to mobile application and web application". This seems to be a one-off cost, meaning no further expenses are to be expected to keep the system operational.

Compatibility

The wristband may be in the way of other devices worn around the wrist.

3.5.2 Cat Smartband

The Cat (Caterpillar) smartband (*Figure 3.30a*) tracks a range of measurements (*Figure 3.30b*) to predict workers' fatigue levels throughout the shift (Jackson, 2016). Indicated by a number between 0 and 100, workers or fleet management can see who is at risk of impairment due to fatigue. The Cat smartband makes use of the SAFTE model and FAST software to generate predictions. The band can also be used for interventions aimed at improving workers' sleep patterns. The smartband can be combined with the Driver Safety System that uses a camera for real-time sleep detection (Mining Global, 2015).

Figure 3.30.
The Cat Band system
(www.cat.com/en_US/75riv
eab/safetyservices/products
/smartband.html)
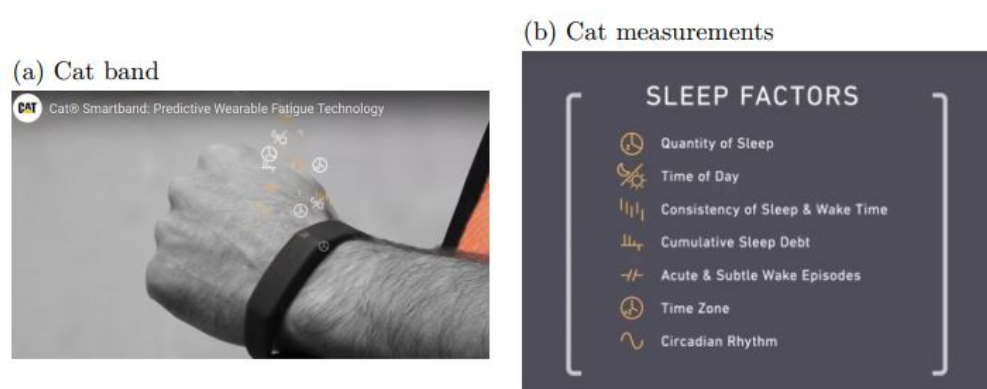
Validity

A search with Google Scholar yields several mentions of the system (Carter, 2016; Haskins, n.d.), but all involve fairly broad descriptions of the system and the importance of fatigue management.

Intrusiveness

Some workers may not prefer to wear a wristband, but overall the system cannot be considered to be physically intrusive.

Availability

Supported by Caterpillar, an important player in the construction industry sector, the system can be expected to be available now and in the future.

Robustness

The device uses a 3D accelerometer, and should therefore not be affected by sweating.

Acceptability

The acceptability of the system will depend on whether workers agree on wearing the device away from work, which may provide the employer with knowledge about workers' activities in their own time. The real-time camera system (DSS) will have the same possible privacy issues as other camera systems).

Sustainability

The Smartband can be expected to have similar sustainability as fitness monitors, although a consideration is that for the system to work, a monthly contribution will be needed.

Cost

The Smartband costs $300 per unit, plus an additional $30 monthly fee per worker.

Compatibility

Unless other wristbands need to be worn, the device will be compatible with other systems.
A possible issue may be that the device needs to be worn away from the job, and may therefore interfere with day-to-day activities or other devices worn around the wrist.

3.6 Fatigue Models

Fatigue models aim to make predictions about a workers' sleepiness based on information such as past sleep (quality, intensity), activities, a person's age, time of the day, type of work, work experience, caffeine intake, or naps taken (Sun et al., 2014). Fatigue models can be used in isolation, or in combination with activity tracker types of devices that measure prior sleep (e.g., Readiband). While they do not monitor fatigue continuously during driving, they may be able to predict periods of increased fatigue and thereby alert drivers or fleet management to take or prescribe a break from driving. We here describe one fatigue model, as similar results have been found for other models (Van Dongen, 2004). Short descriptions of other fatigue models can be found in the *Appendix*. Fatigue models are commonly used in aviation, where time zone differences play an important role. Because of the availability of activity trackers that also include sleep models, they are less likely to play a role in fatigue detection in drivers.

3.6.1 CAS-5

CAS-5 ('Circadian Alertness Simulation') is a fatigue model (www.circadian.com/247-industries/aviation/cas-5-fatigue-risk-model.html) that aims at modelling fatigue in pilots, incorporating the effects of travelling across different time zones. It takes into account three types of factors (Moore-Ede, 2011): homeostatic (built-up of sleepiness), circadian (biological clock and time zones) and sleep inertia (residual fatigue after waking). The model makes use of average alertness levels, duty time with sleepiness, and chronic fatigue scores (Moore-Ede, 2011). The software asks fleet management to send information about crew planning (*Figure 3.31b*). It then takes into account time zones, past sleep information, sleep opportunity information, and computes alertness and risk minute by minute (*Figure 3.31a*; Moore-Ede, 2011).

The model has been extensively tested and compared to other existing models (Dawson et al., 2011; Dijk & Larkin, 2004; Mallis et al., 2004; Roach, Fletcher & Dawson, 2004). Such comparisons suggest that the various models each have their strengths and weaknesses, but that no single

model appears to stand out as superior to the others (Van Dongen, 2004). While fatigue models can only predict the probability of fatigue given the drivers' characteristics and their sleep and wakefulness history, the 10-minute by 10-minute fatigue as measured by a PVT and predicted by the model showed a close correspondence, and model predictions also closely matched other variables, such as subjective performance ratings, sleepiness and tiredness (CASA, 2014; Fletcher & Dawson, 2001b; Mushenko, 2014). Another study, however, found that model predictions were more in line with subjective sleepiness than performance (Fletcher & Dawson, 2001a).

Figure 3.31. The CAS-5 fatigue model
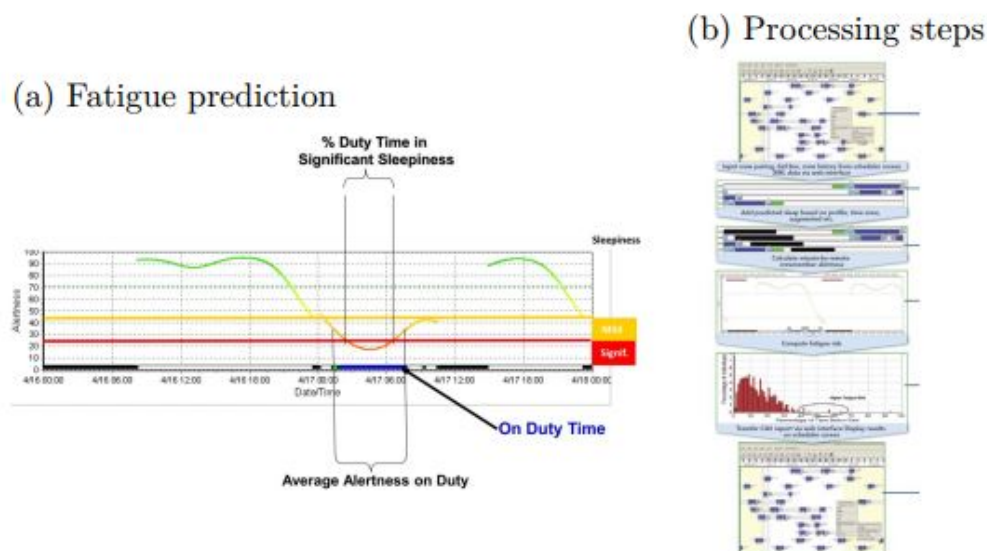
Validity
Models, such as CAS, have been extensively compared to each other (Van Dongen, 2004) and to other measures of fatigue such as PVT (Fletcher & Dawson, 2001b). The model's performance depends on the quality of the input (e.g., information about shift times, sleep times, activities). The quality of this information depends on correct input from the worker. While fatigue models can operate on their own, they may perform better in combination with an activity tracker, such as Readiband.

Intrusiveness
CAS appears to require only information about workers' shift hours, and therefore does not require information about the workers' personal life. It does not interfere with driving, because an assessment is made before the start of the shift.

Availability
The software can be purchased from www.circadian.com/247industries/aviation/cas-5-fatigue-risk-model.html. The CAS-5 version focuses on pilots, and may therefore be less suitable to drivers.

Robustness
The model will only produce predictions on expected fatigue during the shift, and will therefore not measure fatigue on a moment by moment basis. Distraction is not predicted.

Acceptability
If workers' schedules are being fed into the model by fleet management, and workers are given adequate recommendations on their fatigue levels (somewhat in line with their subjective fatigue levels), the system is likely to be accepted. Possibly, a combination with a fitness-to-work test

may aid acceptability: If the model predicts the worker is too tired for work, an additional direct measurement of fatigue may help convince the worker.

Sustainability
The model has been on the market for over 20 years (Moore-Ede, 2011), and there are no reasons to believe it will be discontinued any time soon.

Cost
CASA (2014) indicates to 'Contact supplier for cost details'.

Compatibility
No compatibility issues are to be expected.

3.7 Temperature monitoring

Only one device was found that uses body temperature to measure fatigue. A possible reason is that the link between core body temperature and fatigue is not as clear as for other physiological measures, such as skin conductance and heart rate. For example, subjective sleepiness was found to relate to core body temperatures, but the link with actual sleepiness in terms of the wake-sleep cycle was less clear (Monk, 1987). An increase in body temperature was found in elderly poor sleepers during periods of constant wakefulness (Lushington, Dawson & Lack, 2000). Another study, however, found that core body temperature did not differ between patients with chronic fatigue and control subjects (Hamilos et al., 1998).

Body temperature is unlikely to provide an accurate real-time measure of fatigue during driving. The most accurate measure of core body temperature is obtained using a pill with a temperature sensor that needs to be ingested, which is an invasive method to record a measure of fatigue that is not extremely reliable. More likely applications of temperature sensors in the form of a pill are therefore in the medical domain, for example to monitor people with infections.

3.7.1 Bodycap

Supplier Bodycap has two systems on the market: (1) a patch that can be worn on the body or in a wristband ('eTact'), (2) a temperature sensor in the form of a pill ('e-Celsius Performance', *Figures 3.32a* and *3.32b*). In an e-mail response, the supplier indicates that only the e-Celcius system has been tested in the context of fatigue detection. The specific lab studies have tested the effects of fatigue and jet-lag on driving performance. More common applications are high-performance sports. The device that will be scored here is the e-Celcius pill.

Figure 3.32. e-Celcius body
temperature monitor

(a) e-Celsius temperature sensor

(b) e-Celcius analysis

Validity

A search of the scientific literature for the system did not yield any results. It is also unclear how well core body temperature predicts fatigue. The circadian cycle has been associated with variations in skin and core body temperature (Gradisar & Lack, 2004; Van den Heuvel et al., 1998), but the change in body temperature tends to be gradual and subject to a delay with respect to the onset of sleepiness. The relationship with cognitive fatigue (rather than sleepiness) is less clear. Distraction is unlikely to be measured by the system.

Intrusiveness

The temperature sensor is rather intrusive. It takes the form of a pill that needs to be ingested. It is unclear how long the system will actually measure core body temperature while the pill goes through the digestive tract. The website suggests an operational duration of 20 days, but with a transit time of the human digestive tract of around 1 to 2 days, it is unclear whether the system needs to be recovered and reused for continuous use.

Availability

The temperature sensor can be ordered directly from the supplier or from another webshop (www.mindtecstore.com). bmedical.com.au lists the device under the category 'discontinued', but there are no other indications that the system may not be on the market for long.

Robustness

It is unclear at which stages during the trajectory through the digestive system the core body temperature is reached and whether the device may be susceptible to body movement, bowel movements or fluid intake.

Acceptability

The system is unlikely to be accepted by workers. First, it is fairly intrusive, and second, it will also operate outside working hours, which may lead to privacy concerns.

Sustainability

Operational duration is said to be 20 days (100 days on stand-by), but it is unclear how this duration is achieved in the context of the transit time of the human digestive tract of around 1 to 2 days. For longer-term use, it seems that the pill (which seems to be supplied with a device to read out the measurements) needs to be repeatedly purchased.

Cost

The pill costs around $65 (www.mindtecstore.com, www.cieonline.co.uk). It would therefore be a relatively low-cost solution, if effectiveness and acceptability were not an issue.

Compatibility

High magnetism environments may cause the device to move, but such environments are not expected during normal driving.

3.8   EEG systems

Sleep and the effects of sleep deprivation are typically studied using EEG (brain wave) measurements using electrodes on the scalp (Armitage, 1995; Borbély et al., 1981), which therefore often serves as the gold standard. Changes in the delta (1–3 Hz), theta (4–7 Hz), and alpha (8–12Hz) activities were found to be associated with fatigue, drowsiness, and poor task performance (Lin et al., 2014; Mabry et al., 2019; Sahayadhas, Sundaraj & Murugappan, 2012).

In sleep research, most commonly so-called wet EEG measurements are used, where the skin is prepared with a conducting gel to enhance recordings from electrodes placed on the scalp. For detecting driver fatigue in real-world conditions, preparing the skin and applying conducting gel is not feasible.

Recent developments of so-called dry EEG equipment (Arnin et al., 2013; Ko et al., 2015), where electrodes are directly placed onto the skin without conducting gel have shown sufficiently high correlations with wet systems (>90%, Lin et al., 2014) in non-laboratory situations. In combination with wireless transmission, EEG now seems to provide a feasible method to detect driver fatigue in real-world settings, although systems are only just being brought to market.

There have been claims that brain signals may be detected using equipment inside a head-rest (Kreezer, 2019), but there is no literature that suggests that reliable measurements can yet be obtained in this manner (the same seems to hold for measuring heart rate, which is also best done with skin contact). While contact between the electrodes and the skin may make wearing (portable) EEG uncomfortable during longer shifts, there are indications that systems that are embedded inside a cap do not suffer from this possible downside.

Table 3.8 provides an overview of portable and remote EEG systems for fatigue and distraction detection. Two of these systems (smart cap and B-alert) can be embedded inside a cap and will therefore be more acceptable than the two other dry EEG systems (Emotiv and DSI 10/20) that use more electrodes and cover a larger portion of the scalp. The Freerlogic system that is embedded inside a head-rest is unlikely to produce reliable detection. While there are suggestions that EEG systems may also detect distraction, the main application will be fatigue detection.

Table 3.8. Scores for systems using EEG recordings

Device	Validity	Intrusiveness	Availability	Robustness	Acceptability	Sustainability	Cost	Compatibility
Smart Cap	+	−	++	+	−	+	NA	−
B-Alert	++	−	++	+/−	−	++	+	−
Emotiv	++	−	++	−	−	+/−	+/−	−
DSI 10/20	+	−	+	+	−	+	−	−
Freerlogic	−	+	−	−	+	−	NA	+

3.8.1 Smart Cap

The Smart Cap (www.smartcaptech.com) system consists of a band with five electrodes that can be fitted inside a cap, a hard hat, or can be worn without a hat (Malar et al., 2012; *Figure 3.33a, 3.33b*). Using Bluetooth (*Figure 3.33c*), the system transmits the EEG recordings for further processing to an external unit. There is an option to send the alerts to fleet management (*Figure 3.33d*). The system also provides a display (*Figure 3.33e*) that indicates, with a number between 1 (alert) and 4 (fatigued), whether the driver should take a break.

Researchers from India tested the system in five drunken and five sober drivers and noted differences in the EEG signals recorded in the two groups, but did not perform classification of the participants with these signals to establish how well the system can distinguish the two groups of drivers (Malar et al., 2012). Mabry et al. (2019) indicate that the system has also been tested by researchers from Monash University, comparing a behavioural measure of sleepiness (Oxford Sleep Resistance Test) with the Smart Cap score (both at a 1-4 scale). A 95% sensitivity and 82% specificity was found for the highest score of the Smart Cap (Mabry et al., 2019). The same study is mentioned by Dawson et al. (2014). Another study at the University of Chile confirms that the Smart Cap could be used for EEG measurements (Mabry et al., 2019). These results could not be found, and appear to have been shared in a personal communication. Both reports could not be found in a Google search. Dawson et al. (2014) suggest that the cap is comfortable to wear, while also indicating that the system was not yet commercially available, Mabry et al. (2019) (five years later) do list it as 'currently on the market'. The system will detect fatigue, but not distraction.

Figure 3.33.
The Smart Cap system

Validity

Two reviews (Dawson et al., 2014; Mabry et al., 2019) mention two independent studies of the system, but an internet search did not yield access to the documents. Mabry et al. (2019) indicate that one of these studies suggests a 95% sensitivity and 82% specificity to detect fatigue at the highest levels of the Osler test, but this suggestion could not be verified.

Intrusiveness

The system needs to be worn while driving, in the form of a cap, hard hat, or a headband, and a Bluetooth unit needs to be worn or carried. Dawson et al. (2014) suggest that the cap is comfortable to wear. Malar et al. (2012) also suggest that a reference electrode may need to be attached to the ear. Information from one of the commissioners suggests that after wearing the cap for a long time, the electrodes may start to become uncomfortable on the skin. Another possible concern may be that drivers may think that their employer is 'reading their mind' with the device, or that the electronics near their brain may have negative effects.

Availability

The system is currently commercially available (www.smartcaptech.com).

Robustness

Mabry et al. (2019) suggest that the system works day and night and in rainy and dry weather. How sweating or head movements affect the recordings, is unclear. EEG recordings tend to be influenced by blinking or facial movements, but it is unclear whether Smart Cap compensates for such interference. Interference from blinks and facial movements do not need to be an issue for dry EEG systems such as Smart Cap, because studies comparing dry and wet EEG systems show that filtering of the EEG signal can compensate for such interference.

Acceptability

Acceptability will depend on how comfortable and reliable the system is (in particular the false alarm rate). Not all drivers may want to wear a cap or have the results sent to fleet management. Drivers may also worry about their mind being read, or about the electronics placed close to their brain.

Sustainability

The system has been brought to market between 2014 (Dawson et al., 2014) and 2019 (Mabry et al., 2019). There are no indications it should not be around in the foreseeable future.

Cost

No cost information could be obtained. It may be expected that if few systems are purchased, the system will be expensive, but with more units, the price per unit will go down.

Compatibility

The system will be incompatible with other devices worn around the head. It is unclear to which extent the system is compatible with headphones or glasses.

3.8.2 B-alert

The B-alert system (Advanced Brain Monitoring) uses dry lightweight EEG sensors that can be fitted into a cap or hat, as shown in *Figure 3.34*. Kerick et al. (2013) indicate that, for fatigue and mobile phone distraction, it is one of few systems that analyses the EEG signals real-time, producing an auditory warning signal if an event is detected (Smith, 2007).

The supplier indicates to have tested the system in truck drivers, and that the main issue that was encountered was not the reliability or comfort of the device, but acceptability: drivers did not want to wear a cap or hat while driving. Particularly older drivers did not want to wear the cap, while the field test also suggested that these were the drivers most at risk of fatigue related road

crashes due to sleep apnea. Another application that arose from the field study was the use of the device for fatigue awareness training. Objective and subjective fatigue are not always fully aligned and the device could aid drivers to better recognise fatigue.

The system has been extensively evaluated in developer studies, laboratory studies, and directly compared to other established fatigue measures and driving performance (Dawson et al., 2014). In these studies, it was found that the system provides higher scores after prolonged wakefulness and positively correlates with lapses during a psychomotor vigilance task (PVT), subjective sleepiness, objective sleepiness on the maintenance of wakefulness test (MWT), memory test performance, driving simulator performance, human scored EEG activity and observed sleepiness (Dawson et al., 2014). The supplier indicates that for some drivers false positive rates lower than 1% could be obtained, but not for all drivers.

Earlier versions of the system had to be re-applied every four hours (Dawson et al., 2014) and were therefore more suitable for clinical applications than for driver fatigue detection, but more recent tests with the system show promise in this latter domain, as indicated by the supplier.

Figure 3.34.
The B-alert system
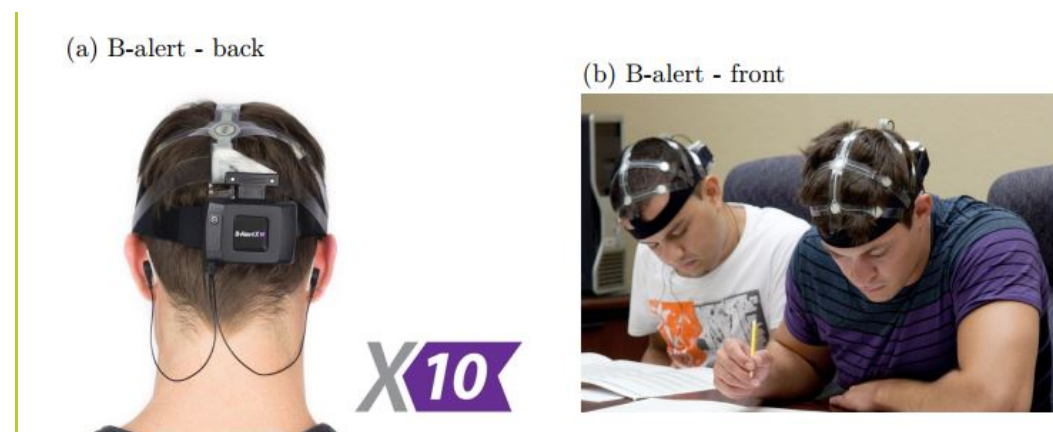
Validity
The system has been extensively validated (Berka et al., 2005; Brown, Johnson & Milavetz, 2013; Dawson et al., 2014; Mitler et al., 2002) in laboratory studies. These studies show that the system is sufficiently reliable for EEG recordings. The system has also been tested in unpublished field studies by the supplier.

Intrusiveness
The system needs to be worn as a cap by the driver, but does not involve wires. Dawson et al. (2014) suggest that it needs re-positioning every four hours, which may make application during long shifts less plausible, but this may only be the case for the version that was available in 2014. Kerick et al., (2013) suggest that the device may become uncomfortable when worn for an extensive period of time (many hours), but this may also refer to an older version of the system.

Availability
The system is not currently offered as an off-the-shelf solution for fatigue detection, as a field test suggested low acceptability in older drivers. The supplier, however, has indicated that they would be able to produce larger numbers of devices if a party were interested.

Robustness
No data appear to be available on how robust the system is against sweating, dust, different head sizes, different hair-styles, and driver movements. The supplier indicates that false detection rates can vary across drivers.

Acceptability

In a field study, drivers did not always accept the system, and particularly older drivers were hesitant to adopt the device. When contrasted with camera systems recording the driver (e.g., Nauto, Guardian), which are likely to be more of an issue with respect to privacy than an EEG device (unless drivers think their mind is being read), such concerns may grow smaller. Drivers may be uncomfortable wearing the cap in a public setting, for example when visiting a restaurant during a break from driving, but can easily take the hat off during those periods.

Sustainability

The system has been on the market for around 20 years. The system is supported by a staff of around 50 people, who provide e-mail and phone support.

Cost

The supplier indicates that if the product is purchased on a large scale, the cost per item could be reduced towards the $350 - $500 range. For a single purchase, it will be in the order of thousands of dollars.

Compatibility

The system will not be compatible with other hats or caps that need to be worn during the shift, unless the device is fitted inside those hats or caps.

3.8.3   Emotiv

The Emotiv EEG system is shown in *Figure 3.35*. It uses 14 electrodes in the form of a headband with extensions for further electrodes (*Figure 3.35a*). A YouTube video on the Emotiv website (www.emotiv.com) suggests that the device can be used to measure distraction in drivers. In a test drive with several drivers, it was found that handsfree calling reduced attention by 4%, texting by 22%, handheld calling by 27% and checking Facebook by 43% (*Figure 3.35c*). Eating and drinking were also found to reduce attention (*Figure 3.35b*). If attention levels dropped below a certain level, a warning light would turn from green to red (*Figure 3.35d*).

Various studies have demonstrated that the Emotiv system can be used to measure EEG (Badcock et al., 2013, 2015; Duvinage et al., 2012, 2013; Ekanayake, 2010; Stytsenko, Jablonskis & Prahm, 2011). For example, the Emotiv device was found to reliably measure late auditory ERPs (e.g., P1, N1) over the frontal cortex (Badcock et al., 2013), and although traditional EEG systems were found to record stronger and cleaner EEG signals than the Emotiv device, processing of the signals allowed the Emotiv system to be used for EEG recordings (Stytsenko et al., 2011). Ekanayake (2010) reached a similar conclusion, indicating that while EEG can be recorded with the Emotiv system, the quality of the signal is not as good as with traditional EEG systems. Duvinage et al. (2012) also found that the system actually measures EEG and not just artifacts, but that it sometimes performs significantly worse than traditional EEG systems. The device was also found to work in children (Badcock et al., 2015). Boutani & Ohsuga (2013) indicate that the device samples at a fluctuating sampling rate, but this could be compensated for in the analysis.

While the suppliers have conducted a small scale study, which they discuss in a YouTube video on their website, there appear to be no peer-reviewed scientific evaluation studies of how well the device can detect fatigue or distraction. The device costs around $750 (Stytsenko et al., 2011). Whether the device is comfortable when worn for a long time is unclear It looks to be less comfortable and is less alluring than the systems that can be fitted inside a cap.

*Figure 3.35. The Emotiv
dry EEG system*

(a) Device

(b) Driver with device

(c) Distraction sources

(d) Warning signal

Validity

The system has been extensively evaluated for measuring EEG under lab conditions, where it has been shown to accurately measure EEG signals after appropriate filtering of the signals (Badcock et al., 2013, 2015; Duvinage et al., 2012, 2013; Ekanayake, 2010; Stytsenko et al., 2011). Whether the device is appropriate to detect driver fatigue and distraction is less clear. There is a YouTube video on the supplier's website suggesting a test performed in a small number of drivers, but no systematic or peer-reviewed evaluation of the system's use for fatigue and distraction detection appears to be available. A brief test with the system in a driving simulator was performed at the University of Lincoln, UK (personal communication), but the system was rather difficult to set up in this setting.

Intrusiveness

The device requires drivers to wear futuristic-looking equipment on their heads. Transmission to a computer is wireless, but probably requires the laptop or computer to be installed inside the vehicle.

Availability

The system can be ordered from www.emotiv.com/epoc/.

Robustness

The system is expected to suffer from extensive driver movements, but no detailed information about this influence could be found. How the system is affected by sweating is also unclear.

Acceptability

The device is unlikely to be accepted by commercial drivers, because of the way it looks and possible restrictions on movements during driving.

Sustainability

The system uses a battery that may require recharging at times. Whether the software requires regular updating is unclear. Quite some signal processing may be needed, which make commercial applications with the current version unlikely.

Cost

The 14-sensor version costs $799, but a 5-ive sensor version is available for $299. Costs may be lower if a large number of devices is purchased.

Compatibility

The system will not be compatible with hats or caps that need to be worn during the shift. How easy it is to put the device back on after a restaurant break is unclear.

### 3.8.4 Dry Sensor Interface (DSI) 10/20.

The Quasar Dry Sensor Interface (DSI) 10/20 (www.quasarusa.com/products_dsi.htm) is a dry sensor EEG system that uses 21 electrodes to measure brain activity (*Figure 3.36*). The website reports that the system is comfortable to wear (for up to 8 hours), needs no setting up, can measure EEG through hair, is quick to set up and remove. The system is wireless, shielded against environmental noise, uses technology to reduce motion artifacts, and runs on battery for at least 24 hours. The website reports correlations with more traditional (wet sensor) EEG recordings of around 80%. The system is mentioned in several peer-reviewed publications (Kang, Ojha & Lee, 2015; Lee et al., 2013; McDowell et al., 2013; Mihajlović et al., 2014) and at least one study demonstrates that the system could reliably record EEG for participants on an exercise bike (Kohli & Casson, 2015). It requires wearing a rather large headband with electrodes (*Figure 3.36a*). The current version does not seem to have software for fatigue or distraction detection.

Figure 3.36.The Quasar dry EEG system
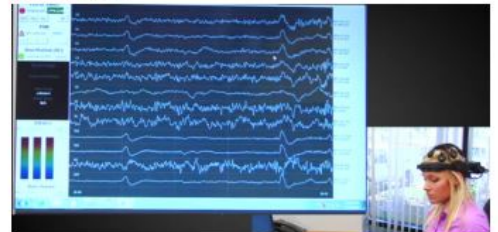
Validity

The system has been validated for the measurement of EEG while on an exercise bike (Kohli & Casson, 2015). It is unclear whether the device can reliably detect distraction or fatigue with the right software extension.

Intrusiveness

The device consists of a fairly large headband and electrodes and is likely to interfere with normal driving (*Figure 3.36*).

Availability

The system can be ordered from bio-medical.com.

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Robustness

The system has been shown to function when cycling, suggesting it is robust against movements and sweating (Kohli & Casson, 2015).

Acceptability

The device is unlikely to be accepted by drivers as a continuous fatigue detection device because of its size and appearance.

Sustainability

The device will operate on batteries for 24 hours. It is unclear how much maintenance it would require.

Cost

bio-medical.com lists a cost of over $22,000, but it is likely that this amount will be less for a large order.

Compatibility

The device will fit inside a helmet. It may be susceptible to signals from mobile phones.

3.8.5 Freerlogic system

The Freerlogic system, developed by Peter Freer, is illustrated in *Figure 3.37*. Two products are offered that both seem to measure brainwaves (*Figure 3.37b*): A headrest to be placed inside a car (*Figure 3.37a*) and an armband to be placed on the upper arm (*Figure 3.37c*). The system is suggested to replace more traditional EEG systems that require the user to wear a cap with electrodes and wires.

Whether the system is actually available is unclear. When trying to look up the website (freerlogic.com), a blank page appears. More information about the system has been found elsewhere on the web (Kreezer, 2019). Here is it suggested that brain activity is measured from the headrest and that, from this brain activity, algorithms then deduce whether the driver is stressed, relaxed, drowsy, fatigued, distracted or emotional (*Figure 3.37b*).

Figure 3.37.
The Freerlogic system
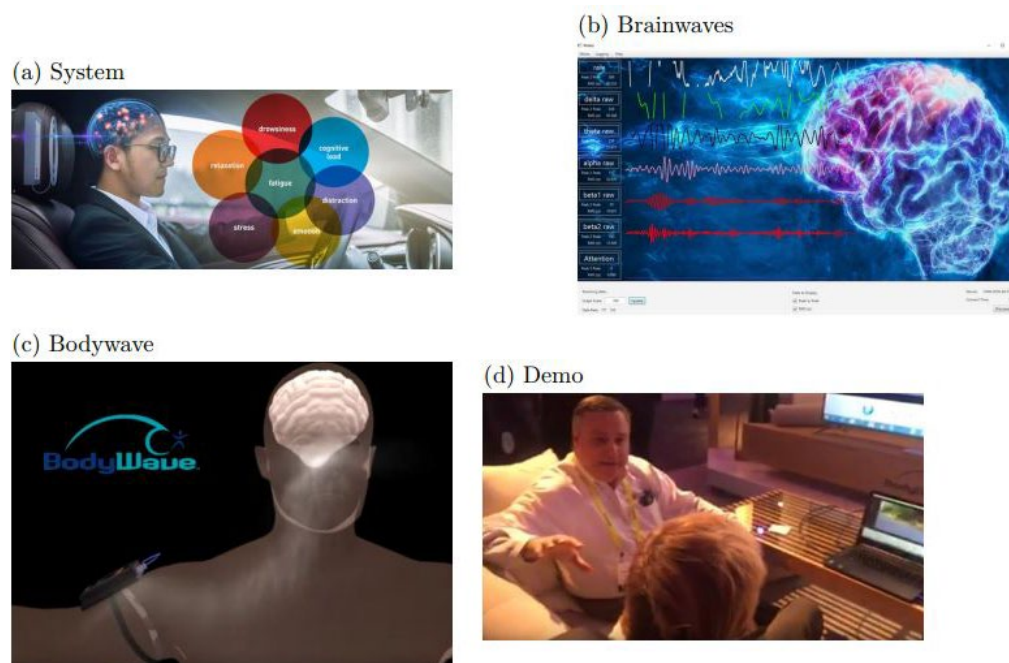
Validity

No information about the performance of the system is available. Contactless EEG recording from longer distances (i.e., not electrodes near the skin) does not appear to be possible. There are two papers that discuss contactless EEG measurements, but they still use electrodes positioned close to the skull (Fernandes et al., 2009; Svärd, Cichocki & Alvandpour, 2010). These papers were published around a decade ago, and there does not seem to be follow-up work that makes use of this technology. There is a YouTube video (Zennie62, 2017) that shows a user trying to focus in front of the headrest, showing a green bar on the screen going up when the user is focusing on the video image of a driving scene. Exactly how this is achieved is unclear, and whether it indeed makes use of signals from the headrest or eye movement signals instead is uncertain.

Intrusiveness

If contactless EEG recordings worked, this would be a substantial improvement over the cap normally needed. The driver could simply enter the car without having to install anything or start a system (assuming the system is placed inside the headrest instead of the armband). The system would be locked to the car and would be difficult to use in a different setting (although the demo in the video seems to suggest it would also work outside a driving situation)

Availability

The website is currently not available, and it is unclear whether it will become available. Peter Freer can be found on LinkedIn, but not directly contacted.

Robustness

If the device were able to accurately record brain signals, it would still be unclear whether such recordings would be robust against head movements that normally occur while driving. Most EEG recordings are sensitive to eye movements (Corby & Kopell, 1972) and head movements (O'Regan, Faul & Marnane, 2013).

Acceptability

If drivers are told that the device 'reads their mind' (Kreezer, 2019), this may raise concerns, even if no recordings are stored, but simply analysed to provide warning signals.

Sustainability

The system does not seem to be currently available, so no information about long-term availability is available either.

Cost

There is no information about the cost of the system.

Compatibility

Because the system is placed inside the headrest, it would not interfere with other systems. Systems that emit electromagnetic signals may interfere with the Freer system. The armband version could interfere with other systems that need to be worn around the arm.

3.9 Skin conductance

Skin conductance was found to be used to measure fatigue in two systems (*Table 3.9*). The sensor has the form of a ring worn by the driver around one or two fingers. While some studies suggest a link between skin conductance and fatigue as measured by a vigilance reaction time test (Inkeri, 2010; Kamensky, 2004), other studies do not find such a link between skin conductance and driving performance, reaction times, and subjective ratings of fatigue (Dorrian et al., 2008). The StopSleep device appears to be the more promising device of the two (*Table 3.9*), but generally skin conductance does not seem to provide an accurate measure of fatigue and does not measure distraction.

Table 3.9. Scores of systems using skin conductance

Device	Validity	Intrusiveness	Availability	Robustness	Acceptability	Sustainability	Cost	Compatibility
EDVTCS	−	−	+	+/−	+	++	−	−
StopSleep	+/−	+/−	+	+/−	+/−	+/−	+/−	+/−

3.9.1 EDVTCS

Several of the fatigue reviews (Dawson et al., 2014; Kerick et al., 2013; NHVR, 2019) mention the Engine Driver Vigilance Telemetric Control System (EDVTCS) system (*Figure 3.38*), developed and made available by Neurocom, based in Russia. The system measures the driver's skin conductance and has been used quite extensively in train drivers. One independent validation of the system did not find sufficient evidence that skin conductance can be used to measure fatigue (Dorrian et al., 2008), which was also confirmed in the review by Dawson et al. (2014), who indicated that although the system had been independently validated in lab conditions (i.e., studies exist), there was little evidence that the system could accurately detect fatigue (the studies did not seem to indicate that the system worked well).

Figure 3.38. The EDVTCS system (images from the Neurocom website and Dorrian et al. (2008)
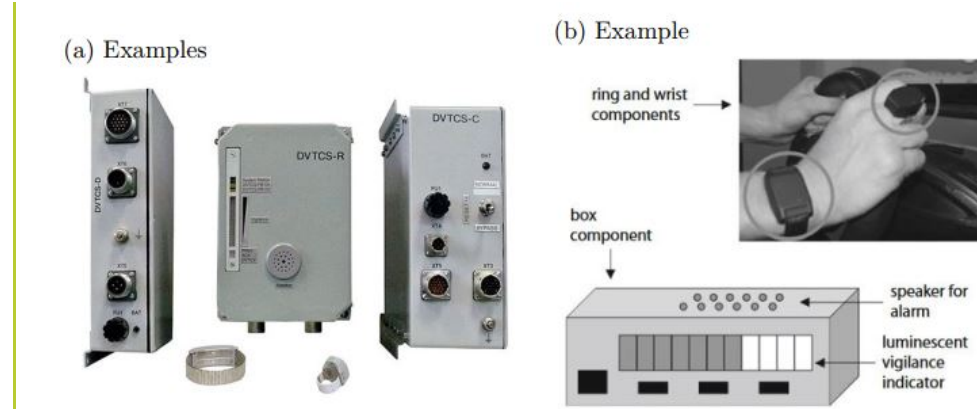
Validity

While an article on the Neurocom website (Kamensky, 2004) suggested that the system worked well, an independent lab study only found weak links between fatigue as measured with other measures and skin conductivity as measured with the EDVTCS (Dorrian et al., 2008). Since the 2008 study, no new evaluations of the system seem to have been carried out. Based on Dorrian et al. (2008), the system does not seem to be highly reliable.

Intrusiveness

The system requires the driver to wear a watch and a sensor around the finger (*Figure 3.38b*). While the watch appears to be comfortable, the sensor around the finger may interfere with

using the steering wheel. Note that the system has been developed mostly in the context of train driving, where a firm grip on a steering wheel may not be required.

Availability
The system is available through the Neurocom website (http://www.neurocom.ru). Because no clear indications of the validity of the system were obtained, no inquiries were made about large scale availability of the system.

Robustness
The one independent lab study of the system did not find good evidence of the validity of the system (Dorrian et al., 2008). It is unlikely that the system will perform better in real-world conditions than in a lab situation, although better performance in train driving than car driving cannot be excluded.

Acceptability
The system seems to underdetect fatigue events, and may therefore be acceptable in terms of absence of false alarms. The section that needs to be worn around the finger may be uncomfortable when worn for longer periods of time, and may interfere with using the steering wheel or gear box.

Sustainability
The system has been on the market for a while and is likely to be available in the foreseeable future.

Cost
Dorrian et al. (2008) indicate the cost of the system to be around € 6,000 per driver.

Compatibility
The section worn around the finger may interfere with driving. It is not immediately clear where the processing unit of the system needs to be installed.

3.9.2 Drover Fatigue Alarm (StopSleep)

The Drover Fatigue Alarm (Mabry et al., 2019), also known as StopSleep, is available from stopsleep.co.uk. It consists of two rings, merged together (*Figure 3.39a*), to be fitted around two fingers of either hand (the FAQ on the website indicates that each combination of two adjacent fingers is fine). It contains eight electrodes (*Figure 3.39a*) that measure skin conductance (electrodermal activity), and uses this to classify the driver's alertness condition into three categories: 'alert', 'microsleep', and 'sleep'. Upon entering the 'microsleep' stage from the 'alert' stage, the device vibrates (*Figure 3.39b*). When entering the sleep stage, the device vibrates and produces a warning sound. The video suggests this second warning is the signal to take a break from driving.

Figure 3.39. The StopSleep device (images from the video on stopsleep.co.uk)

The website suggests that a recent scientific study conducted in France claims that drivers wearing StopSleep devices could prevent more than 800 deaths per year. It then moves on to talk about 'the test driver' (suggesting that the test involved a single driver) in the study, who had

accumulated 6 minutes of sleep on his journey from Paris to Lyon without being aware of this sleep, suggesting that the number quoted was based on a single journey of a single driver.

www.stopsleep.com.au provides further information about the scientific tests and reports two studies: one with 20 participants (measuring EEG, eye movements – using SR Research's Eyelink 1000 device, and skin conductance with two StopSleep devices in a sustained attention task distinguishing treble or bass sounds for 30 minutes) and one with 10 participants (with a similar setup as the first, but this time to determine the false positive rate of the device). The website suggests that the device accurately distinguishes between alertness and sleep, but without giving numbers to back up the results. The device therefore appears to have been tested in 30 participants under lab conditions, and one driver under real-world driving conditions.

The FAQ suggests that the device is comfortable and does not interfere with driving, which, in the video, is illustrated by the driver moving his hand with the device to switch gears. When switching the device between drivers, it has to be reset, so it measures each driver's individual skin conductance. Mabry et al. (2019) indicate that it takes between 3 to 5 minutes for the device to calibrate). The device uses a blinking green light to indicate that it is measuring skin conductance, and a red light to indicate that there is an issue with measurements (e.g., when the hands are cold). The device's battery needs to be recharged every 10 hours, which can be done with an in-vehicle charger (charging takes around 1 hour). Auditory signals will indicate when the battery levels are low. Mabry et al. (2019) indicate that the device costs around $199 for just the device and $293 for the device, chargers and warranty. Mabry et al. (2019) report that the log of the device can be loaded onto a computer for further inspection using a USB connection.

Validity
Some independent (CNRS, France) validation of the device appears to have been performed, but details about the results (e.g., false alarm rate) are not available.

Intrusiveness
The website indicates that the device does not interfere with driving and that drivers may forget wearing the device over time. The device itself is a large ring that needs to be fitted over two fingers, so it is unclear to which extent this is really the case. The device may hinder holding the steering wheel with a strong grip.

Availability
The device can be purchased from various versions of the StopSleep website, for example, from stopsleep.co.uk. It no longer is in a development stage.

Robustness
Mabry et al. (2019) indicate that the device does not work under cold weather conditions. The FAQ on the website also indicates it may not work well over cold skin. How hand movements, and in particular grasping with the two fingers that hold the device, affects measurements is unclear. Whether the device fits well for all hand sizes is also unclear.

Acceptability
There appear to be no studies about acceptability of the device. If the device is as comfortable as the website suggests it is, it is likely to be acceptable to drivers. No information is sent to fleet management (although they may ask for the log stored on the device), and vibration as a first warning signal does not seem too intrusive. Whether the device will be accepted, will also depend on the false alarm rate, about which little information is provided.

Sustainability
The device needs to be charged every 10 (website) to 15 (Mabry et al., 2019) hours. Charging takes 1 hour. How long the device lasts until it needs to be replaced is unclear. There are no indications that the device will be discontinued any time soon.

Cost
The device is said to cost between $199 and $293 (Mabry et al., 2019).

Compatibility
The device will not be compatible with any other systems that need to be worn around the fingers. It will not be compatible with wearing gloves, and cannot be used in cold weather (Mabry et al., 2019).

3.10   Fitness-for-duty tests

An important class of fatigue detection systems are fitness-for-duty tests. Although these systems do not continuously monitor for fatigue, and do not measure distraction, there are several features that make them attractive, including good validation, low cost and high acceptability. Fitness-for-duty tests can be combined with other systems.

Fitness-for-duty tests are typically performed before the start of a work shift and, on the basis of the results, a decision is made whether the worker can start the shift. Systems can make use of reaction times, tracking movements, or eye movements, but they all have in common that they are used before the start of work. If the system is portable (and affordable, so that each driver can carry one) it can also be used during breaks, but otherwise fitness-for-duty systems do not measure fatigue while driving.

As advantages of fitness-for-duty tests Dawson et al. (2014) list (1) that workers are not monitored during work (which they may resist) and (2) that such tests do not require the installation of equipment inside the vehicle, or the driver wearing equipment (see also Hartley et al., 2000). As possible downsides, Dawson et al. (2014) indicate that there is no good evidence that the tests predict subsequent fatigue (i.e., only fatigue at the start of the shift), and that workers can take stimulants to pass the test while they actually should be resting. Kerick et al. (2013) suggest that for fitness-for-duty tests (and in particularly the psychomotor vigilance test) the link between tests scores and other sources of fatigue-related performance changes, such as declining motivation or prolonged exposure to stressors, is poorly understood. The same authors also indicate that the tests have relatively low predictive accuracy, and particularly struggle to predict variations across individuals (Kerick et al., 2013). The tests also do not pick up changes in a worker's state during the shift (Hartley et al., 2000). Likewise, NHVR (2019) concludes that fitness-for-duty tests are not suitable for ongoing detection or monitoring driver fatigue.

Tests can make use of various types of signals and responses, such as pupillary responses, reaction time measures, or tracking accuracy. Some systems can also include information about past sleep (e.g., measured with an activity tracker, or information supplied by the driver), caffeine intake, time spent on the job, or time of the day. Sometimes, such measurements and information are combined with a mathematical sleep model, such as the SAFTE model (Brown, 2012). Fitness-for-duty tests that use sleep models show promise, but is has been argued that they can be improved by relying on process-oriented methods instead of curve-fitting (Kerick et al., 2013), and by actual sleep measurements with activity bands.

Advantages of fitness-for-duty tests are that they are often systematically and scientifically evaluated, do not interfere with driving, and tend to be acceptable for drivers (as no devices need to be worn or cameras need to be used to monitor the driver). Disadvantages are that they

only measure fatigue at the start of the shift (or after a break), that they may be cheated by use of stimulants such as caffeine, and do not measure distraction. *Table 3.10* provides an overview of fitness-for-duty tests. The PVT test has been tested extensively, and is often used as a baseline measure in fatigue studies. A further advantage of the PVT is that a free version is available. The PVT relies on reaction times, which may be more susceptible to influence from the user (intentionally slowing their responses) than, for example, tracking movements (OSPAT) and pupil measurements (FIT).

*Table 3.10. Scores of fitness-for-duty systems and fatigue models*

Device	Validity	Intrusiveness	Availability	Robustness	Acceptability	Sustainability	Cost	Compatibility
FIT	+	+	+	+/−	+	++	+/−	+
Fatigue-o-meter	+/−	+	++	+	+	++	+	+
OSPAT	+	+	+	+	+	++	++	+
PVT	++	+	++	++	++	++	++	+
EyeCheck	−	+	−	−	+/−	−	+/−	
2B-Alert Web	+/−	++	++	−	+	+	++	+/−
Pulsar informatics	+	+	+	+/−	+/−	+	+	+
DriveABLE	++	−	+	+/−	−	++	−	+

3.10.1 FIT

The Fitness Impairment Tester (FIT) is another fitness-for-duty test. It is available from www.pmifit.com. The current model is called FIT 2000-3 (*Figure 3.40b*), and, like older versions (e.g., *Figure 3.40a*), makes use of saccadic velocity and pupil restriction (pupil diameter, constriction amplitude and latency), each compared to an individual's baseline values. The test is said to take around 30 seconds and cannot (easily) be faked. It thereby takes substantially less time than the often used PVT, which takes at least 3 minutes. The device appears to be rather large (*Figure 3.40*) and may therefore have the downside that it cannot be moved easily for testing during breaks.

Several peer-reviewed validation studies show that saccadic velocity and pupil restriction latency are both linked to sleep deprivation, subjective levels of sleepiness, psychomotor 93riveable test lapses, driving simulator accidents and scores on neurocognitive tests (for an overview, see Dawson et al., 2014). Some small sample field studies were also conducted showing increased FIT scores towards the end of long shifts (see also Dawson et al., 2014). The website refers to additional field studies ('by demanding customers'), without providing further details. It also indicates that the device operates under different lighting conditions, offers saccade detection at 750Hz and pupil measurements with a 0.022 mm resolution.

Figure 3.40. The FIT systems (images taken from www.pmifit.com)

(a) FIT 2000-2

(b) FIT 2000-3
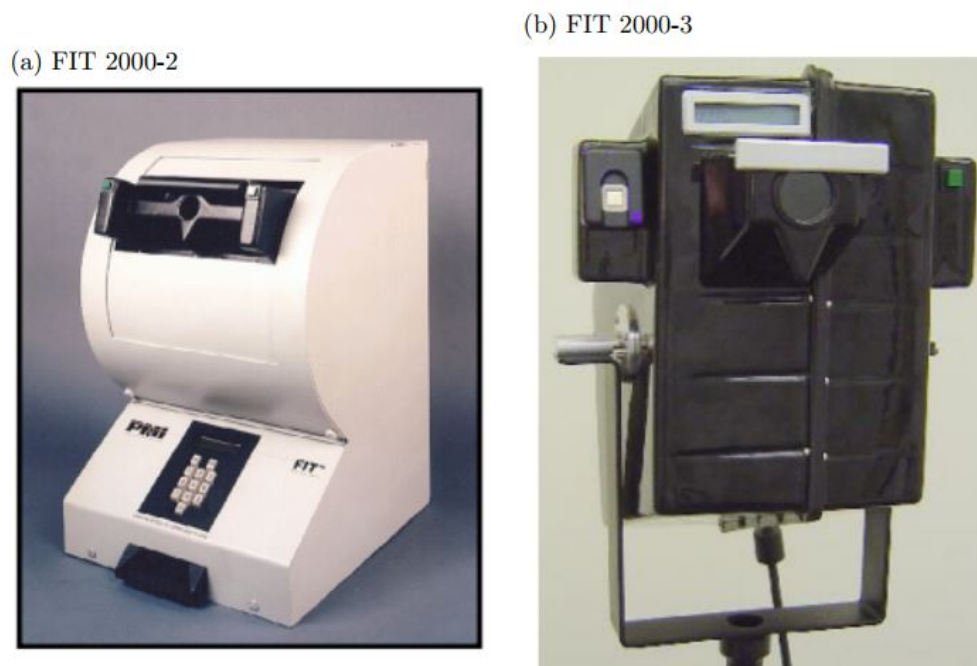
Besides measuring fatigue (both due to monotonous driving and sleep deprivation), the device can also detect the effects of legal medications, illegal drugs, alcohol, and sleep deprivation, alone or in combination (pmifit.com). Dawson et al. (2014) suggest that more field studies are needed, as only two of the four measures (saccadic velocity and pupil restriction latency) have been shown to be reliably linked to fatigue, and the device may not work well in people with excessive blinking or thick corrective lenses.

As the FIT test is performed before the start of the shift, it does not provide continuous fatigue monitoring. It is unclear whether the device can be used while on the move (during breaks), and whether the cost would be sufficiently low to allow for an individual device for each driver. The device does not measure distraction.

Validity
The device has been tested extensively in laboratory studies (Balkin et al., 2004; Kalich et al., 2006; LeDuc, Greig & Dumond, 2005; Loving, Kripke & Glazner, 1996; Van Dongen, Caldwell & Caldwell, 2006), but further field testing would be required, particularly in older drivers (Dawson et al., 2014). It appears that most studies of the device were performed around 2010, and it is unclear whether the newer model of the device has the same performance as the device tested in 2010.

Intrusiveness
The device does not interfere with driving, as the test is performed before the start of a shift (or if it is sufficiently portable, during breaks).

Availability
The device can be ordered from the website www.pmifit.com.

Robustness
The device is said to work under different lighting conditions, and detects a range of causes that could lead to impaired driving, including fatigue, alcohol intoxication, and drug use (www.pmifit.com). There may be problems with older drivers, drivers who blink excessively, and drivers wearing thick glasses (Dawson et al., 2014).

Acceptability

The test is said to take only 30 seconds and involves looking at a series of dots (www.pmifit.com). The FIT score was found to agree with subjective measures of fatigue (Dawson et al., 2014), which makes its results easier to accept.

Sustainability

The system has been on the market for more than a decade, and it is likely to be available in the foreseeable future.

Cost

The website indicates the cost per test to be low (www.pmifit.com), but it is unclear how much the device itself would cost.

Compatibility

The device does not seem to work well in drivers that blink often or wear thick glasses (Dawson et al., 2014), but no other compatibility issues appear to exist.

3.10.2 Fatigue-o-meter

The fatigue-o-meter is available from the website www.fatigueometer.com. It is a computerised spatial perception (mental rotation of an image of a person holding a bell) and reasoning test (Kerick et al., 2013). The test takes around one minute to complete and compares performance (reaction times) with the individual's usual baseline. This baseline adjusts with continued use of the test, ensuring the test remains valid over time. The test was introduced in 2006 and has undergone development since.

The website of the supplier describes a field test in collaboration with Subaru, suggesting correlations between fatigue-o-meter test results and driving precision (unclear how this was defined) between 0.40 and 0.50. Reaction times were longer after a tiring driving test. The website also indicates that across 7200 participants the test shows a high reliability of 0.84 (which indicates that the results are consistent, but does not automatically imply external or construct validity). This number of participants has since increased to around 1.4 million (personal communication). The numbers on the website suggest that around 10% of tests result in a fatigue warning. The blog indicates that the test is now available as an Android and a mobile phone (Blackberry and Nokia) application. The test does not continuously monitor fatigue, although the phone version will allow for repeated testing throughout the shift. It does not measure distraction.

Validity

The device does not seem to have been tested in independent, peer-reviewed evaluations (no results in Google Scholar), but some field study results are mentioned on the website. One such test suggests a correlation between 0.40 and 0.50 with driving precision (definition unclear), which indicates a reasonable, but not perfect association. A high reliability (of 0.84) is listed, but this does not automatically mean that the test actually measures fatigue. The test is portable in the form of a phone app, and can therefore be used in breaks as well as before a trip.

Intrusiveness

The test is said to take around a minute to complete. It is taken before the shift or during breaks, and does therefore not interfere with driving.

Availability

The test is available online, and it can be purchased in the form of a computer programme, an Android or mobile phone (Blackberry and Nokia) app.

Robustness

The system adjusts for practice with the task. The user will need to be in a quiet location to perform the test.

Acceptability

Whether the test will be acceptable, will in part depend on how well the test results relate to subjective fatigue. As subjective fatigue is not always a good indicator of actual fatigue, some driver education may be needed to improve acceptability. No information was found on the association with subjective fatigue.

Sustainability

The test was launched in 2006 and still appears to be available, suggesting it will be around in the foreseeable future.

Cost

The app costs around $10 per person per month.

Compatibility

The test can be performed before starting to drive, and therefore does not seem to have compatibility issues.

3.10.3 OSPAT

The OSPAT (Occupational Safety Performance Assessment Technology) test takes around 60 seconds and compares a worker's performance with the average performance of that worker to determine fitness for duty on that day (www.ospat.com). The test determines a worker's fitness to work, but does not distinguish the cause of the lack of fitness (fatigue, stress, illness, some medications, illicit drugs, excessive alcohol use, dehydration, high humidity and high temperatures).

Dawson et al. (2014) suggest that the OSPAT fitness has undergone independent validation, but that such evaluation shows weak evidence of its validity. Petrilli et al. (2005) describe the test as an 'unpredictable tracking task that measures hand-eye coordination'. This paper also refers to a validation of the tracking task, which was not yet called OSPAT at that time (Dawson & Reid, 1997). The purpose of that article was not so much to test the validity of the test, but instead to show that the impairment due to fatigue can exceed that due to alcohol intoxication.

A second validation of the OSPAT (Petrilli et al., 2005) showed a significant correlation between fatigue measured with a psychomotor vigilance task (PVT) and the OSPAT (r = 0.40). A weaker correlation between the OSPAT and fatigue was found in a field study with 193 train drivers, although it is common to find less reliable results in a field study than a laboratory setting (Fletcher & Dawson, 2001a). Reid & Dawson (2001) also used the OSPAT, but not with the aim to validate the device, but instead to test differences between younger and older workers.

Validity

There is reasonable evidence for the OSPAT as an alternative for the psychomotor vigilance test (PVT), with stronger evidence inside the lab (Petrilli et al., 2005; Reid & Dawson, 2001) than in a field setting (Fletcher & Dawson, 2001a), although Dawson et al. (2014) suggest the test may not be sufficiently reliable.

Intrusiveness

The test is performed before the shift starts. It takes only 60 seconds and involves tracking a visual target with a trackball.

Availability

The test is available through www.ospat.com. The vendor responds to e-mail.

Robustness

The test was found to measure impairments due to fatigue and alcohol intoxication (Reid & Dawson, 2001). It does not monitor fatigue in real-time.

Acceptability

The test takes around 60 seconds and does not involve providing personal information of any kind, making acceptability of the test very likely.

Sustainability

The test has been around for some time. The professional layout of the website suggests its supplier intends to provide the service for some time to come.

Cost

The vendor suggests that the subscription cost per week is similar to that of a cup of coffee. In addition a one-off setup fee is charged.

Compatibility

There are no clear compatibility issues to be expected.

3.10.4 Psychomotor Vigilance Task (PVT)

The traditional Psychomotor Vigilance Task (PVT) takes 10 minutes and measures reaction times, lapses (reaction times over 500ms) and error rates. The test is particularly suited to detect sleep deprivation (Basner & Dinges, 2011), but caffeine use may mask such sleep deprivation effects (Van Dongen et al., 2001) and poor performance on the PVT does not always mean poor driving performance and vice versa (Dawson et al., 2014).

Commercial (PalmPVT, PVT-192) and free versions are available (Khitrov et al., 2014; Reifman et al., 2018). The advantage of the commercial version (https://www.cwe-inc.com/products/other-instruments/pvt-192-reactiontimer) is that it is a stand-alone unit that can easily be transported, while the free version requires a computer or laptop. The updated version of the PC software (Reifman et al., 2018) has several additional features including the option to import sleep and caffeine intake schedules into the software, to generate individual predictions, and to visualise the individualised results.

Because 10 minutes is rather long, shorter versions of the test have been developed. Jones et al. (2018) suggest that the shorter 5-minute version of the test yields comparable results to the original 10 minute-version, but the 3-minute version does not.

Studies have also examined whether the test can be performed on other devices, including touchscreens, phones and watches. Arsintescu et al. (2019) found that a touchscreen version of the task yielded similar results to the 5-minute version. Good PVT results were also found for iPhones (Smith, 2019). Results from a wristwatch version of the task were not comparable to those of a laptop version (Matsangas & Shattuck, 2018).

Validity

The psychomotor vigilance test has been tested extensively (for an overview, see Dawson et al., 2014) and various versions, commercial and free (Khitrov et al., 2014; Reifman et al., 2018), have been made available. The link between PVT and driving performance is less clear (Dawson et al., 2014), as is the link between PVT performance and other sources of fatigue than sleep deprivation, such as declining motivation or heat exposure (Kerick et al., 2013).

Intrusiveness

The test is performed before the start of the shift and does therefore not interfere with driving. Commercial versions are available in the form a small unit, and can therefore also be used during breaks. The free version will run on a laptop that may also be used in such a manner.

Availability

The test is available from commercial and free sources. It is one of the most often used tests for sleep deprivation.

Robustness

Dextroamphetamine, caffeine and modafinil were shown to improve performance on the test after sleep deprivation (Killgore et al., 2008; Van Dongen et al., 2001). Daytime exposure to bright light had the same effect (Phipps-Nelson et al., 2003). Sleep deprivation may therefore be masked by stimulants and exposure to bright light.

Acceptability

The 10-minute test may be somewhat long, but the 5-minute test is likely to be acceptable to most drivers. A possible issue may be that the test does not always seem to be predictive of driving performance (Dawson et al., 2014).

Sustainability

The test is available from commercial and free sources. It has been on the market for a long time and can be expected to be available for some time.

Cost

There is a free version (Khitrov et al., 2014; Reifman et al., 2018). The cost of the PVT-192 could not be found.

Compatibility

The test will not interfere with other devices in the cabin.

3.10.5 EyeCheck

The EyeCheck system performs a fitness-for-duty test by examining the user's pupil diameter (Dawson et al., 2014). The website listed by Dawson et al. (2014), eyecheck.com, no longer seems to point to the device, but another website (barenco.com/security-products/eyecheck-pupilometer.asp) does. The link to the general MCJ Eyecheck Website on the page, however, no longer works (the web domain is for sale).

Various articles refer to the test (Chacon-Murguia & Prieto-Resendiz, 2015; Gilbert, 2000), but no systematic tests of the system appear to be available. For the older device, Dawson et al. (2014) indicate that there is no peer-reviewed literature on the validity of the device. These authors also describe a developer test that showed that scores given by the device were significantly lower for truck drivers who reported a maximum of five hours of sleep in the previous night (compared to those who reported more than five hours of sleep), but the scores did not correlate with self-reported fatigue. Dawson et al. (2014) also refer to a study that showed that the EyeCheck could predict an 18-hour period of wakefulness with an 82% sensitivity and a 94% specificity. An online document (EyeCheck, n.d.) provides evidence for the link between EyeCheck scores and illicit drug use.

Validity

Although some evidence appears to be available that points towards the validity of the device (Dawson et al., 2014), the overall evidence is not highly convincing, except possibly the use of the device to detect drug use (EyeCheck, n.d.).

Intrusiveness

The device measures fatigue before the start of the shift and does therefore not interfere with driving.

Availability

The original website no longer exists. There is a website with some information about the device (barenco.com/security-products/eyecheck-pupilometer.asp), but the link to the MJC website no longer works, casting doubts on whether the device is still for sale.

Robustness

It is unclear how well the device works in different drivers (e.g., eye colour, glasses, make-up around the eyes).

Acceptability

Generally, fitness-for-duty tests that are accurate and take little time and effort can be expected to be accepted. A 82% sensitivity may be somewhat low for the test to be acceptable.

Sustainability

As it is unclear whether the device is still sold, it is also unclear how long the device will still be on the market.

Cost

No information could be found regarding the cost of the device.

Compatibility

The device may not work well in drivers with glasses, but no other compatibility issues are to be expected.

3.10.6   2B-Alert Web

2B-Alert Web (2b-alert-web.bhsai.org, Reifman et al. (2016), Reifman et al. (2019), *Figure 3.41*) provides an online tool or app implementing the psychomotor vigilance test (PVT). The tool was developed by the United States Army Medical Research and Materiel Command. It allows users to manually enter a sleep, wake, and peak alertness schedule, and information about caffeine intake. On the basis of this information, using a performance model (Rajdev et al., 2013; Ramakrishnan et al., 2016a; 2016b) and caffeine model (Ramakrishnan et al., 2014), the tool will predict alertness and optimal caffeine intake moments.

The website indicates that the system is for educational and informational purposes only and should not be used to assess individuals. The article (Reifman et al., 2016) indicates that this is because only group averages can be accurately predicted by the model, and the effects of caffeine intake and sleep deprivation vary across individuals. It also indicates that the performance model was developed for PVT measures in laboratory conditions, which may impair performance of the model outside the lab.

Validity

The tool has been developed to predict group averages, and for PVT performance inside the lab. For these purposes, the model has been validated (Rajdev et al., 2013; Ramakrishnan et al., 2014; Ramakrishnan et al., 2016a; 2016b). The website indicates that the tool cannot be used to reliably predict individual performance and the article by Reifman et al. (2016) suggests that the tool may be less reliable for conditions outside the lab. The tool will only asses fitness to work, and does not provide continuous monitoring of fatigue. It does not detect distraction.

Intrusiveness

The tool can be used before the start of a shift, either as a web-tool (Reifman et al., 2016) or phone app (Reifman et al., 2019). It will therefore not interfere with driving performance.

Availability

The tool can be used online or downloaded as an app. Since it is an educational tool, support may be limited, and it is unclear how long the tool will be available.

Robustness

The tool has been developed for PVT performance inside the lab and may therefore be less suitable for predicting performance outside the lab.

Acceptability

The tool appears to be flexible in how much information the user needs to enter about sleep deprivation or caffeine intake, but it may become less accurate if such information is missing. As such, the tool can be expected to be acceptable for drivers.

Sustainability

The tool will be available for as long as the web-page hosting the tool will continue to do so. It is also unclear whether the app will cater for future versions of the operating system.

Cost

The tool is available for free.

Compatibility

The tool will be compatible with other devices needed while driving, as it will only be used at the start of the shift. A device with an internet connection and web browser will be needed for the

online version (Reifman et al., 2016). The app will work on phones using iOS and Android (iPhone 6s and iPad Air 2 running iOS 9.3+ and Samsung Note 4 running Android 6.0.1+; Reifman et al., 2019).

3.10.7 Pulsar Informatics – Fatigue Meter

Pulsar Informatics (pulsarinformatics.com) provides a fatigue management solution and fitness-to-work tests (*Figure 3.42*). Two products are offered: an online psychomotor vigilance test (PVT) and the Trucking Fatigue Meter, which makes use of the Electronic Logging Device (ELD) inside the vehicle (and therefore does not require the installation of equipment that is not yet already required in vehicles in the US). It provides an alert when the driver's fatigue levels exceed a threshold.

Figure 3.42. Pulsar Informatics – Fatigue meter

Validity

The psychomotor vigilance test (PVT) has been extensively validated (Drummond et al., 2005; Graw et al., 2004; Lamond, Dawson & Roach, 2005; Roach, Dawson & Lamond, 2006). The supplier ensures accurate timing of the test over the internet. The mechanisms behind the Trucking Fatigue Meter are less clear.

Intrusiveness

As a fitness-for-duty test, the product does not interfere with driving. It will not continuously monitor for fatigue. The Trucking Fatigue Meter is said to provide this continuous monitor without additional equipment that may interfere with normal driving.

Availability

The products are commercially available and no longer in a stage of development.

Robustness

Since the PVT is run in a web browser, an internet connection is required. The PVT will run on various systems, including iPads, but not Android tablets. There is less information about how robust the Trucking Fatigue Meter is.

Acceptability

Drivers may have difficulties being confronted with their sleep patterns and quality. The truck driver case study on the website suggests that the employer and the worker should together work towards a solution if sleep difficulties are detected by the system. The Trucking Fatigue Meter does not require the use of cameras, which will alleviate some of the privacy concerns. The false alarm rate is unclear.

Sustainability

Since the product relies on a web browser, it can be expected to be functional for a long time, as long as the product is available. The same holds for the Trucking Fatigue Meter, which may additionally require that the sensors inside vehicles do not change to such an extent that the product can no longer interface with them.

Cost

The Trucking Fatigue Meter will cost around $5 per month per driver, and discounts are available for large fleets and multi-year contracts.

Compatibility

The online PVT test will be compatible with other devices, such as navigation, as it involves testing before work. The Trucking Fatigue Meter is not expected to interfere with other systems.

3.10.8 DriveABLE

DriveABLE (www.driveable.com) is a university spin-off that focuses on driver assessment. It offers three products: DCAT (a cognitive assessment tool), DORE (on road evaluation of cognitive skills) and ExceleRATE (driver assessment program).

The DCAT product is a plug-and-play system with a touch screen and a 3-button base that presents six tasks that measure cognitive processes needed for safe driving and is predictive of on-road performance. It measures motor speed and control, attentional span and shifting ability, coordination of mental abilities, spatial judgement, identification of driving situations and decision making. As such, it measures general ability to drive and to a lesser extent fitness-to-drive just before the onset of a shift.

DORE focuses on cognitive impairments and compares driving errors in a test subject's driving test with healthy drivers. ExceleRATE provides an all-in-one driver risk management programme to assess drivers on their skills for safe driving, specifically focusing on assessing whether drivers with a medical condition or on medications are fit to drive.

Validity

The DORE driving test outcomes were compared to an in-office assessment (102riveable) in 3662 patients. An 1.7% error rate was found for pass predictions (false negatives) and a 5.6% error rate for fail predictions (false positives; Dobbs, 2013), suggesting that the in-office assessment may suffice to determine whether it is safe for patients to drive. Another comparison of 52 drivers with the in-office 102riveable assessment found an error rate of 3% for fail predictions, with a 90% specificity and a 76% sensitivity (Korner-Bitensky & Sofer, 2009). The 102riveable test also showed good test-retest reliability (with κ values of 0.654 – all 39 participants, and κ = 0.742 for stroke patients, Korner-Bitensky et al., 2011). The DCAT test was also found to be accurate in assessing the fitness-to-drive of stroke patients (Choi, Yoo & Lee, 2015). The test, however, assesses whether an older driver or driver with a health condition is fit to drive, and it is unclear whether the same predictive performance is obtained when using the test to assess driver fatigue. It is likely that differences between fit-to-drive older drivers and those not able to drive are larger than those between alert and fatigued drivers, and that the test may be less able to pick up the latter type of differences. Those assessed, however, have complained that the test may have a too low pass rate (MetaFilter, 2012).

Intrusiveness

The test has six tasks and is said to take around 20 to 30 minutes to complete (MetaFilter, 2012). As such, the task may therefore not be suitable as a fitness-to-drive test for fatigue.

Availability

The test can be purchased via the supplier's website (www.driveable.com). It lists a large number of partnered institutions (albeit relatively small and local), suggesting the products will be available longer term.

Robustness

As an in-office fitness-to-drive test (DCAT), the product does not have difficulties with factors such as heat, dust or impacts. It is unclear how well the test performs on healthy, but possibly fatigued drivers.

Acceptability

The long duration (20-30 minutes) and low pass rates (15% in those who need to be tested, MetaFilter, 2012) may make the test less acceptable.

Sustainability

It can be expected that the test will be around for a sufficient amount of time.

Cost

The costs are unclear. Someone on MetaFilter (2012) suggests the test is expensive.

Compatibility

The product is not expected to interfere with normal driving, but the long testing time and focus of the test on assessing patients rather than healthy individuals is likely to render the product unsuitable for fatigue detection.

3.11 Steering movements

Devices that measure fatigue on the basis of steering movements tend to require the installation of some equipment inside the vehicle. This can, however, be as simple as attaching a sensor to the steering wheel. Devices that use steering movements have the advantage that they do not interfere with driving and can therefore expect to have high acceptability with the drivers (as long as the false positive alarm rate is low).

Studies have suggested that with increased fatigue, drivers show increasing amplitude of steering wheel reversals (Lupova, n.d.). More subtle changes in steering movements may also be detected and used to assess driver fatigue by using machine learning methods (Sahayadhas, Sundaraj & Murugappan, 2012; Sayed & Eskandarian, 2001). The use of such machine learning methods yielded an 89.9% drowsiness classification accuracy (Sayed & Eskandarian, 2001). Moreover, when drivers fell asleep during simulated driving, the analysis of steering movements could detect drowsiness 3.5 minutes before a crash (Sayed & Eskandarian, 2001), providing sufficient time to intervene. Furthermore, fatigue detection in a simulated driving environment using steering wheel movements worked as well as the more established PERCLOS measure (McDonald et al., 2014).

The issue with steering movements, however, is that under real-world driving conditions, drowsiness detection tends to be worse, due to steering corrections needed for uneven road surfaces (Friedrichs & Yang, 2010). Similar issues were reported in studies by car companies that used steering wheel angles (Sahayadhas, Sundaraj & Murugappan, 2012).

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Table 3.11 lists the various systems that use steering wheel movements and their scores on the criteria. The main concern with the two systems in this table is that it is unclear how susceptible they are to bumpy road conditions and to other possible reasons of changes in normal steering movements under real-world driving conditions (McDonald et al., 2014; Sayed & Eskandarian, 2001).

Table 3.11. Scores of systems that use steering movements to detect fatigue

Device	Validity	Intrusiveness	Availability	Robustness	Acceptability	Sustainability	Cost	Compatibility
ASTiD	+/−	+	+	+/−	+	++	NA	+
Bosch / Mercedes	−	+	+	+/−	+	++	NA	+

3.11.1 ASTiD

The ASTiD system from Fatigue Management International (*Figure 3.43*, fmiapplications.com) consists of two components: (1) a knowledge-based system that takes into account factors such as time of day and circadian rhythm, and (2) a steering sensory system that detects monotonous driving and steering manoeuvres indicative of fatigued driving (Mabry et al., 2019). These two components are described as 'complex signal processing' and 'predictive, approximation algorithms' by the company's website. The first component predicts the likelihood of the driver falling asleep in the next 24 hours, while the second component uses monotonous driving and steering characteristics. Four indicators are used: (1) time of day, (2) sleep quality, (3) length and type of driving, and (4) vehicle steering corrections. Because of the two components, the ASTiD system can be considered a hybrid system (operator centred and vehicle centred), which generally offers better performance than single principle systems (Kerick et al., 2013). The two systems approach may be needed, as drowsiness detection in real-world driving conditions from steering wheel movements alone has shown to be difficult (McDonald et al., 2014; Sayed & Eskandarian, 2001).

Mabry et al. (2019) list the device as 'unvalidated' as the website does not provide information on how the device functions in different environments. Kerick et al. (2013) appear to be more positive, and indicate that the ASTiD system was one of only three systems out of twenty-two ready for implementation in an operational environment, based on a review by Caterpillar Safety Services (see also Golz et al., 2010). Dawson et al. (2014) indicate that no validation studies are available for the system. Edwards et al. (2007) list the device in their review, but do not seem to provide a score. Butlewski et al. (2015) mention the system as an example, but do not provide an evaluation.

No further information could be obtained from the company directly: the website does not list contact details other than a contact form, which does not seem to work. In isolation, steering behaviour was found to distinguish between slight and strong fatigue with an 86% accuracy (Krajewski et al., 2009), and a systematic investigation of predictions of six mathematical models of fatigue showed that they can predict several sleep-wake scenarios well, but struggled with two chronic sleep scenarios (Van Dongen, 2004). Together, fatigue detection and prediction may yield better results than the isolated contributions of both systems.

*Figure 3.43.
The ASTiD system (from
fmiapplications.com)*

Validity

There appear to be no systematic independent evaluations of the system. The two underlying mechanisms (steering behaviour and mathematical models of circadian rhythms) appear to both predict fatigue fairly well. In combination, they could be a powerful predictor of fatigue (Kerick et al., 2013), but without validation studies, this is difficult to determine.

Intrusiveness

The system has been designed for low intrusiveness, by making use of sensors already incorporated in the vehicle.

Availability

The supplier has a well maintained website, Twitter, Facebook and LinkedIn accounts, but the contact form does not seem to be working. The product has been on the market for a while.

Robustness

It is unclear whether the system will work under all circumstances. Mathematical models of sleep patterns were found to fail in certain chronic sleep scenarios (Van Dongen, 2004). It is unclear to which extent steering movements from rough surfaces is similar to steering movements that suggest fatigue. Drowsiness detection in real-world driving conditions from steering wheel movements alone was found to be difficult (McDonald et al., 2014; Sayed & Eskandarian, 2001).

Acceptability

Unless the system has high false alarm rates (which will depend, apart from the accuracy of the system, on the threshold level to trigger a warning), it can be expected to be acceptable to workers, because it only tracks steering movements. It is not exactly clear what information workers need to provide for the first component of the system (knowledge-based system). Admitting a poor night's sleep may sometimes be problematic.

Sustainability

There are no indications that the system will not be around for the foreseeable future.

Cost

Because the system makes use of internal vehicle sensors, the cost may be low, but from the website it is unclear whether it is.

Compatibility

There are no reasons to believe the system may interfere with other systems in the vehicle.

3.11.2   Bosch Driver Drowsiness Detection / Mercedes Attention Assist

Bosch Driver Drowsiness Detection and Mercedes Attention Assist appear to be almost identical and will be described together. Both systems make use of a steering angle sensor (*Figure 3.44*). From the movements of the steering wheel and 70 other signals from inside the car, both systems collect information about factors such as the use of other in-car systems, the road surface condition, and duration of driving.

Together, these sensor signals are used to predict driver fatigue. First, steering behaviour at the start of the journey (when the driver is assumed to be alert) is compared with later behaviour. Steering behaviour associated with fatigue are 'phases during which the driver is barely steering, combined with slight, yet quick and abrupt steering movements to keep the car on track' (www.bosch-mobility-solutions.com). When fatigue is detected additional information about the length of a trip, use of turn signals, and the time of day is used to determine whether the steering behaviour is actually a sign of fatigue or something else (www.fjmercedes.com). A cup of coffee signal on the instrument panel warns the driver to take a break.

Arnin et al. (2013), Hamid et al. (2016) and Jabbar et al. (2018) all refer to the device, but only mention that it makes use of steering movements. Various other papers refer to the Mercedes Attention Assist system without information about how well it works (Churiwala et al., 2012; Friedrichs & Yang, 2010; Jabbar et al., 2018; Kerick et al., 2013; Lee et al., 2014). Mabry et al. (2019) lists the device by Bosch as 'unvalidated'.

Figure 3.44. The Bosch Driver Drowsiness Detection system (images from www.bosch-mobility-solutions.com), and the Mercedes Attention Assist system (images from www.youtube.com/watch?v =A66zgJ4Oj8o)
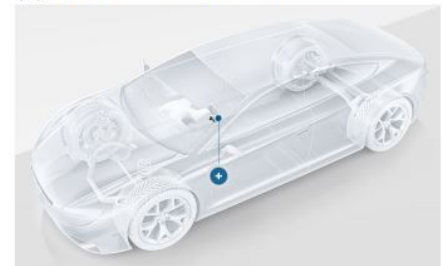
Validity
No peer reviewed evidence of the accuracy of the system could be found. Steering movements have been found to have relatively poor predictive performance under real-world conditions (Friedrichs & Yang, 2010; McDonald et al., 2014; Sayed & Eskandarian, 2001), but possibly the 70 features extracted by the Bosch system aid to outperform such results.

Intrusiveness
The system requires the installation of a small ring around the steering wheel axis. A cup of coffee symbol will need to be added to the instrument panel.

Availability
The system is available from the Bosch website (www.bosch-mobilitysolutions.com).

Robustness

It is unclear how robust the system is against variations in driving behaviour, weather conditions, road conditions, or driving speed.

Acceptability

The system does not require the user to wear a device or a camera facing the driver, and it will therefore be well accepted if the false alarm rate is sufficiently low. The warning signal (a coffee cup) will also easily be tolerated, but may not suffice to warn the driver in case of severe fatigue.

Sustainability

There are no indications that the device could be discontinued any time soon.

Cost

This information could not be provided by the provider for commercial reasons (Bosch).

Compatibility

The device will need to be installed inside the vehicle, but is otherwise not expected to interfere with driving or other devices in the vehicle.

3.12 Eye tracking

Eye tracking is a technology with a substantive history (Duchowski, 2007; Holmqvist et al., 2011; Rayner, 1978; 1998). Rayner (1998) distinguishes three eras of eye tracking research: (1) Early fundamental research revealing the general properties of eye movements, (2) applied research, and (3) a revival of more fundamental research in the context of cognitive psychology, suggesting interest in the topic from both fundamental and applied research. Eye movement recordings have also been used extensively to study driving, for example comparing novice and experienced drivers in different driving conditions (Konstantopoulos, Chapman & Crundall, 2010), investigating attentional processes during lane changes (Salvucci & Liu, 2002), or distraction from mobile phones (Balk et al., 2006; Doumen, Van der Kint & Vlakveld, 2019).

Early eye movement equipment was highly invasive (Buswell, 1935; Yarbus, 1967) often involving placing suction lenses inside the eye (Robinson, 1963). Modern eye trackers tend to consist of infrared cameras and emitters, placed in front of the user, or inside the rims of glasses and can achieve similar performance (Schmitt et al., 2007; Van der Geest & Frens, 2002). Most developers and suppliers of eye tracking equipment (e.g., SR research, Tobii, Positive Science) focus on the research community (fundamental or commercial). Several have been taken over by commercial partners in recent times (e.g., EyeTribe, SMI glasses) after increased interest from virtual reality technology developers, as eye tracking may improve such products by estimating what the user is looking at.

While eye tracking has the potential to detect fatigued and distracted drivers with high accuracy (e.g., from blinking rates, eyelid closure, or gaze directions other than towards the road), only a limited number of systems make use of eye tracking, possibly because accurate eye tracking under real-world conditions is still difficult, and eye trackers tend to be relatively expensive. Systems such as Guardian and EyeSight, that use Infrared cameras and computer vision to analyse driver's eyes and gaze direction may be considered eye tracking technology as such, except that their main focus is not to determine what the driver is looking at, but instead merely focus on the task of detecting driver distraction and fatigue, and use information from both the face, upper body and eyes (while eye trackers only focus on the eyes).

Devices that measure PERCLOS, or use pupil measurements to determine fitness to work, such as Optalert and Eyecheck, also make use of information from the driver's eyes, but do not necessarily

track the direction of gaze and do not perform eye tracking as such. *Table 3.12* provides an overview of eye tracking systems that aim to detect fatigue. From the three devices listed, Smarteye shows the most promise. Given that computer vision systems can detect eye gaze direction, eyelid closure, and various other measures of fatigue and distraction (e.g., head nodding, phone use), and are often less expensive than eye tracking systems, eye trackers may not be the first choice in fatigue and distraction detection.

Table 3.12. Scores of systems that use eye tracking

Device	Validity	Intrusiveness	Availability	Robustness	Acceptability	Sustainability	Cost	Compatibility
SmartEye	+	−	++	+	+	++	+/−	−
Vigo	−	−	+	−	−	+/−	+	−
SmoothEye	−	+	+/−	−	+	−	+	+
Ellcie	+/−	−	+	+/−	+/−	+/−	+	−

3.12.1 Smart-Eye

Based in Sweden, Smarteye (smarteye.se) provides technology that at first seems to be an eye tracker, focused on measuring gaze direction, but that combined with deep learning can be used to detect fatigue and distraction. More information about the device and its application to fatigue can be found in Bretzner & Krantz (2005) and in a white paper (Smarteye, n.d.) available on Smarteye's website. Besides using a standard VGA camera, the system uses two IR emitters (*Figure 3.45a*). These emitters produce a reflection on the corneas of the driver's eyes, which can be used as reference points to estimate gaze direction (Morimoto & Mimica, 2005). By using two IR emitters, issues with reflections from glasses can be eliminated by subtracting the additional reflections.

The white paper (Smarteye, n.d.) indicates that the system uses a 3D model of the head. Combined with facial features (position of the nose and mouth), detected with computer vision algorithms (*Figure 3.45b*) and deep neural networks, the system estimates eye gaze relative to head direction (*Figure 3.45b*, Bretzner & Krantz, 2005). Input for training with the deep neural networks needs to be annotated, but is unclear how such annotation was obtained.

Figure 3.45. Smarteye system (www.smarteye.se). Images extracted from YouTube and (Bretzner & Krantz, 2005)

(a) Camera and IR illuminators

(b) Video analysis
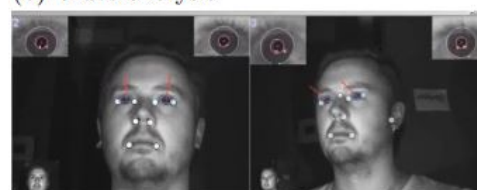
Validity

While Dawson et al. (2014) suggest that the system has not been independently tested, there are some studies that use the hardware (i.e., without the deep learning part). Niu et al. (2013) use the system in combination with a support vector machine to detect fatigue from the recorded eye movement signals, and find an approximate 72% accuracy in detection of sleepiness (but also report large individual differences). Feldhütter et al. (2018) combine the system with a decision tree classifier and report a fatigue detection sensitivity of 90.0% and specificity of 99.2%. Li and Wang (2014) also use the hardware and suggest that particularly the PERCLOS measure of the

system helps predict fatigue. Other reviews mention the system as promising. For example, Edwards et al. (2007) list SmartEye as one of the better fatigue detection techniques. Kerick et al. (2013 describe the device as established, but also note the device may target mostly fundamental research. Mabry et al. (2019) list the device as 'promising' (one category lower than 'established').

Intrusiveness
The system requires three small devices to be mounted on the dashboard: Two IR emitters and one camera, the latter of which needs to be directly in front of the driver. The system will therefore interfere with other systems that need to be placed at these locations. It is unclear how much additional hardware (e.g., a laptop or computer) needs to be installed inside the vehicle for the system to work.

Availability
The hardware has been available for a long time and been used in various validation studies (Feldhütter et al., 2018; Li & Wang, 2014; Niu et al., 2013). How long the deep learning component has been on the market is unclear. Mabry et al. (2019) suggest that alarms that signal fatigue or distraction are not a standard system feature and need to be added upon request.

Robustness
Because the system uses multiple IR emitters, it will also work in darkness and when the driver wears a pair of glasses (Bretzner & Krantz, 2005; Smarteye, n.d.). Hardware evaluation studies (Feldhütter et al., 2018; Li & Wang, 2014; Niu et al., 2013),however, all seem to test the system in driving simulators, and it is therefore unclear how the system performs under real-world conditions.

Acceptability
While the system uses a camera facing the driver, no images appear to be recorded. The acceptability will therefore largely depend on the false alarm rate of the system, which could be fairly low (Feldhütter et al., 2018), although it is unclear how well the deep learning networks perform their task (Smarteye, n.d.).

Sustainability
The commercially available version that includes fatigue detection appears to be fairly recent, and it is unclear whether it would be possible to deploy the system on a large scale in a fleet of vehicles, and how long the system will be available.

Cost
Bretzner & Krantz (2005) specifically talk about a 'low-cost' system, but the actual cost is unclear (Mabry et al., 2019), and may depend on the number of units purchased.

Compatibility
It is unclear how much additional equipment needs to be installed besides the two IR emitters and the camera. The IR emitters may interfere with other equipment that uses IR signals.

3.12.2   Vigo

The Vigo system (www.wearvigo.com) combines measurements of head movements, blink rates, blink durations and drooping eyelids to detect fatigue in drivers (*Figure 3.46*). The website also suggests the device can detect gaze behaviour such as scanning the road and checking side mirrors, monitor whether drivers take breaks, determine whether drivers use their phones, perform harsh braking or acceleration, or display speeding behaviour. The device is sold for $99. The device can be worn in combination with glasses, can be used as a headset, and must be used in combination with a smartphone. The device was mentioned by Alsibai & Manap (2016) and He et al. (2017), but no validation studies seem to be available.

Figure 3.46. The Vigo system
(images taken from
www.wearvigo.com)
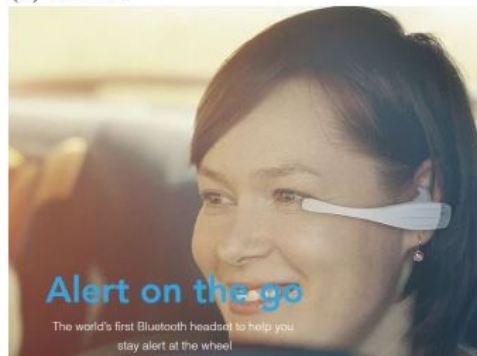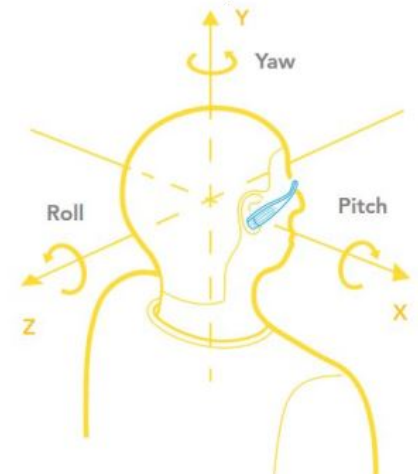
Validity

No information about the performance of the device, or validation studies could be found. The hybrid approach of combining eye and head movements is likely to make the system more reliable than systems that only use one of these signals.

Intrusiveness

The device needs to be placed rather close to the eye and may therefore interfere with driving.

Availability

The device can be purchased from www.wearvigo.com. It is no longer in a development stage.

Robustness

It is unclear how well the device works for different drivers, and whether it will stay in place with head movements.

Acceptability

Drivers may resist using the device, because it may be uncomfortably close to the eye.

Sustainability

It is unclear how long the battery will last and how long the device will be on the market.

Cost

The device costs $99 per unit.

Compatibility

The device is incompatible with other devices worn around the ear, such as headsets.

3.12.3   SmoothEye

SmoothEye (www.smootheye.com) is an eye tracker that can track gaze direction at a frequency of 1000Hz. It consists of light-weight goggles with a head orientation sensor (*Figure 3.47*). By asking users to follow a moving dot on the screen, the system determines whether the user is alert (indicating that an alert person can perform smooth pursuit eye movements, while less alert people will need many corrective saccades). Besides smooth pursuit performance, the system also measures pupil diameter, and fixation behaviour.

A search with Google Scholar suggests that smooth pursuit may be used to detect fatigue (Porcu et al., 1998). However, several other factors have also been shown to affect smooth pursuit

performance, including schizophrenia (Benson et al., 2012; Hutton et al., 1998), stress (Březinová & Kendell, 1977) and aging (Sharpe & Sylvester, 1978). The system on the website appears to be a fitness-for-duty test using eye movements, but the supplier indicates that a version is being developed that monitors drivers' eye movements in real-time (using slow eye movements, head movements, and posture changes).

Figure 3.47. The SmoothEye system (images taken from www.smootheye.com)

Validity

No validation studies were found. While some studies suggest a link between drowsiness and smooth pursuit performance (Porcu et al., 1998), several other factors may have a stronger link, such as schizophrenia (Benson et al., 2012), and stress (Březinová & Kendell, 1977). The supplier indicates the system is in a development stage and it has not been evaluated for accuracy yet.

Intrusiveness

The system described on the website can be used before starting to drive. The newer system that monitors for fatigue in real-time requires a camera to be installed inside the cabin.

Availability

The system is available www.smootheye.com. The supplier suggests the device is still under development, but available for purchase (see 'cost').

Robustness

Generally, eye tracking tends to be less accurate in people wearing glasses (particularly with thick lenses) and rigid contact lenses. Some eye trackers also have issues with large pupil diameters. Whether these factors also influence the SmoothEye system is unclear. A sampling rate of 1000Hz can be considered as high and definitely sufficient to study smooth pursuit eye movements.

Acceptability

The test only takes a short amount of time and does not require using equipment during driving. The acceptability of the real-time version of the device will depend on the false alarm rate.

Sustainability

Eye trackers tend to have a long life-span when used inside a lab. Less clear is whether they will also last in less ideal conditions with dust, heat, and humidity.

Cost

The supplier indicates the retail price to be around $150.

Compatibility

The system is used before driving and therefore does not interfere with other equipment needed for driving.

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3.12.4   Ellcie smart glasses

The Ellcie smart glasses (ellcie-healthy.com) have 15 sensors (*Figure 3.48*), including four infrared sensors around the eyes that help detect events such as blinking, eye movements, head nodding and yawning, which are then combined to detect fatigue and distraction. Unclear is how this is exactly done, and how reliable fatigue detection is. A mobile phone app will show the overall output of these sensors as a stream of information (*Figure 3.48*) and will send a warning message to a designated person if there are clear signs of fatigue in the person wearing the glasses, in addition to a warning light starting to blink. The glasses can be ordered for around $300 from the website.

Figure 3.48. The Ellcie smart glasses. Images from a YouTube video demonstrating the glasses

(a) Glasses

(b) Phone app
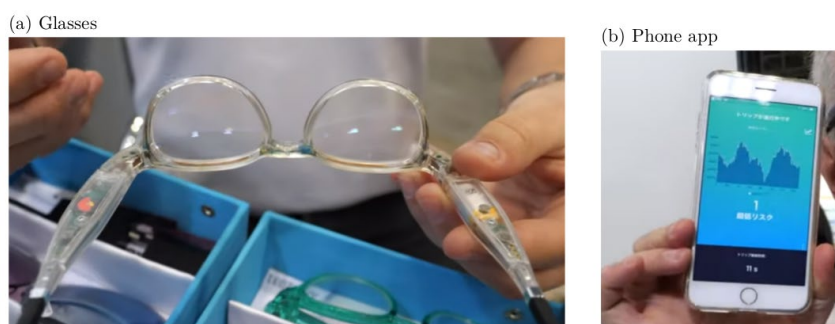
Validity
The system is described in three conference proceedings (Arcaya-Jordan, Pegatoquet & Castagnetti, 2019a; 2019b; 2020), but these are concerned with energy consumption of the batteries rather than the accuracy of fatigue detection. No other indicators were found of how well the device detects fatigue or distraction.

Intrusiveness
Users will have to wear a pair of glasses with a rather thick rim. These may somewhat restrict the view of the driver.

Availability
The system can be ordered from ellcie-healthy.com. It is unclear whether large numbers can be purchased simultaneously.

Robustness
The glasses can be fitted with dark lenses (sun glasses) and prescription lenses. It is unclear whether the system works for different people (e.g., different normal blinking rates), or whether it is susceptible to lighting conditions.

Acceptability
Not every driver will accept having to wear a pair of glasses. This may be less of a problem for people normally wearing glasses or sunglasses. The glasses may weigh more than a typical pair, which may be a concern for longer term use. The recorded signals appear to be sufficiently unclear to a human observer to cause privacy concerns.

Sustainability
The device appears to be in a relatively early stage of development. It is unclear how long the system will be on the market, and how much maintenance the glasses will need. Battery life may be a concern.

Cost
The glasses are a low-cost solution, costing around $300.

Compatibility

People already wearing glasses would need to fit prescription lenses. The device can easily be turned into a pair of sunglasses.

3.13 PERCLOS systems

An often used and effective measure, which has been adopted in systems for a fair amount of time, is the method of detecting to which extent the driver's eyelids are closed. Initially, this measure was scored by human annotators, who estimated the percentage of eyelid closure (termed PERCLOS) from the images. Later, automatic recognition software was developed that can automatically estimate PERCLOS from moving driver images. With the PERCLOS measure, fatigue is said to occur when at least 80% of the eyelid is closed (Dinges et al., 1998; Murawski et al., 2013; Wierwille & Ellsworth, 1994; Wierwille et al., 1994).

While PERCLOS is an effective eye movement measure to detect fatigue, other measures such as eye blinks, eye gaze patterns and pupil diameter have also been suggested, and combinations of measures appear to outperform measurements of PERCLOS alone (Kerick et al., 2013). Various studies have demonstrated the validity of the PERCLOSE measure. For example, when comparing the PERCLOS measure with two EEG algorithms, two eye blink monitors, and a psychomotor vigilance task (PVT), Dinges et al. (1998) found that PERCLOS strongly correlated with the PVT results (correlation around 0.90) and demonstrated better coherence than the other measures. A later study that used machine learning techniques for classification of fatigue state on the basis of EEG measurements or PERCLOS suggested that the EEG measurements better distinguished between mild and strong fatigue (Sommer & Golz, 2010). A similar conclusion was reached by Trutschel et al. (2011) who, in the title of their paper, therefore described PERCLOS as 'an alertness measure of the past'. In practical applications, however, PERCLOS may be more acceptable to users than, for example, EEG. The latter requires participants to wear a cap with electrodes, which may become uncomfortable when worn for extensive amounts of time (although two newer systems on the market, SmartCap and B-alert, may be more comfortable; see *Section 3.8*).

To overcome the possible limitations of using PERCLOS to predict fatigue, systems can combine the PERCLOS with other eye movements features, such as blink frequency. This strategy is used by the Optalert system, which combines blink frequency, velocity and duration to score fatigue on the Johns drowsiness scale (Johns & Hocking, 2015; Stephan et al., 2006), which strongly correlates with more traditional reaction time measures of drowsiness (Johns et al., 2007; 2008).

Table 3.13 shows the systems that use PERCLOS as their main method of fatigue detection. PERCLOS cannot be used to measure distraction. Across the different PERCLOS systems, Optalert has the best validity, availability and sustainability. However, the system requires wearing glasses. It may be outperformed in terms of acceptability by computer vision and eye tracking systems that can also measure PERCLOS, blink frequency and blink velocity.

Table 3.13. Scores of systems that use PERCLOS to detect fatigue

Device	Validity	Intrusiveness	Availability	Robustness	Acceptability	Sustainability	Cost	Compatibility
Optalert	++	+/–	++	+	+	++	–	+/–
DD850	+/–	+/–	+	+/–	+/–	+	+	+

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3.13.1 Optalert

The company Optalert (www.optalert.com) currently offers two products: Eagle industrial, and Eagle portable. Both consist of a wireless set of glasses (*Figure 3.49a*). While the industrial version is connected to a small display (*Figure 3.49b*), the portable makes use of a mobile phone. Using small cameras inside the rims of the glasses, the system detects to what extent the eyelids are closed (PERCLOS) and how fast the eyelid opens after it has closed (www.optalert.com). Jackson et al. (2016) suggest that six additional ocular variables are extracted.

Fatigue is measured on the Johns Drowsiness Scale, and the score is shown in the display. When high levels are observed, there is an auditory warning to the driver and fleet management is alerted. The glasses can be fitted with prescription lenses and turned into sunglasses, but this requires each device to be used by one driver only (so that lenses do not have to be changed). The website indicates that the product has been on the market for over 20 years, during which continuous development has taken place.

The effectiveness of PERCLOS and Johns drowsiness scale, both used by the device, has been demonstrated in a range of studies (Anderson et al., 2011; Corbett, 2009; Ftouni et al., 2013a; 2013b; Howard et al., 2011; Jackson et al., 2016; Liang et al., 2019; Stephan et al., 2006). The device was also used to study circadian rhythms (Ftouni et al., 2015), the effects of Ramadan fasting on drowsiness (BaHammam et al., 2013), the effect of caffeine and drowsiness and driving errors (Aidman et al., 2018; Michael et al., 2008), motivation to take a break when tired (Williamson et al., 2015), and driver education (Alvaro et al., 2018). The device's ability to detect fatigue was also demonstrated in pilots, who, compared to drivers, need to look around the cabin more. The Optalert glasses are reportedly well tolerated in users, but may not work optimally for drivers with sleep or visual disorders (for an overview, see Dawson et al.,2014).

Figure 3.49. Optalert glasses and display (from video on www.optalert.com)
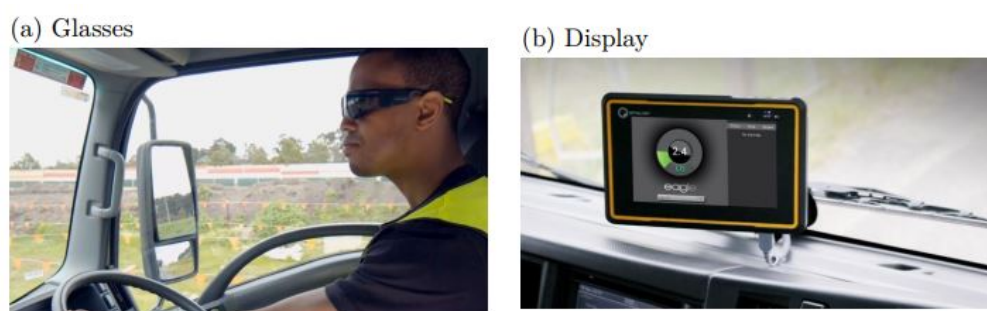
Validity

The system has extensive peer reviewed support (Dawson et al., 2014; Jackson et al., 2016; Liang et al., 2019).

Intrusiveness

The system requires the driver to wear glasses and is therefore somewhat intrusive. A small unit needs to be placed on the dashboard, but a version exists where this unit is replaced by a mobile phone. The glasses can be fitted with prescription lenses, so that they can be used by drivers who need to wear glasses.

Availability

The system can be purchased through www.optalert.com. The system has been on the market for 20 years.

Robustness

The system appears to work well for most users, although there are indications it may work less well for drivers with sleep or visual disorders (Dawson et al., 2014). When lighting conditions

change during driving, drivers may need to change the lenses, or take off the glasses (Mabry et al., 2019).

Acceptability
The glasses are lightweight and generally well accepted (Dawson et al., 2014), although under changing lighting conditions, they may need to be taken off to switch to sunglasses (Mabry et al., 2019).

Sustainability
The system has been on the market for some time and there are no indications it will be discontinued any time soon.

Cost
Mabry et al. (2019) list the cost of the system at $1000 per unit, when more than 100 units are ordered. On top of the purchase costs, there is a monthly $20 to $50 subscription fee.

Compatibility
The system takes up little space, but requires the driver to wear a pair of glasses. While prescription lenses can be fitted, quickly switching to sunglasses in changing lighting conditions may cause problems.

3.13.2   DD850 Fatigue Warning System

The history of the DD850 system (*Figure 3.50*) is somewhat unclear. The system that is available from www.nightdrivingsystems.com/dsm/meye/4000.html appears to be a follow-up of the system described by Dawson et al. (2014) as 'co-pilot', originally developed by Carnegie Mellon University. According to the website the device has now been replaced by 'EyeAlert' (eyealert.com). This again does not appear to be the most current version, because under 'specifications', visitors are transferred to another website, with another device (lumeway.com/EA.htm). 'News' on this last website was last updated in 2014, but the vendor still responds to e-mail.

How the system exactly works is not entirely clear. The system appears to work under night-time conditions, suggesting the use of an infrared camera and light emitters (see also *Figure 3.50*). The device is suggested to use PERCLOS by Dawson et al. (2014). A video on YouTube demonstrates the system by a driver trying to pay attention to the road and simultaneously trying to simulate sleep (during actual driving). Two different warning sounds and voice messages can be heard. In the video, the EyeAlert appears to work during daytime, and the concern expressed by Dawson et al. (2014) that the device may only operate during night-time may have been resolved.

One study has used the EyeAlert system for research purposes (Wang, Xu & Gong, 2010), while another appears to suggest that the EyeAlert system outperforms a computer vision system for driver fatigue detection with glasses under night-time conditions (Weng, Chen & Kao, 2008). Others simply mention the system (Addanki et al., 2019; Alsibai et al., 2017; Merat & Jamson, 2013). The supplier indicates that the system now makes use of GPS to avoid triggering a warning message at low vehicle speeds.

Figure 3.50. Various versions
of the DD850 system
over time

Figure 3.50. Various versions of the DD850 system over time

Validity
Dawson et al. (2014) indicate that there is weak evidence to suggest that the device works, although one abstract suggests a link between PERCLOS as measured by the device and the score on Johns drowsiness scale (Howard et al., 2006). Barr et al. (2005) suggest various limitations, such as viewing angle, and performance under daytime conditions.

Intrusiveness
The device needs to be placed on the dashboard (*Figure 3.50*).

Availability
The name of the device and web-address has changed multiple times, but the supplier is still in business and the system is still available.

Robustness
Past reviews suggested that the system works poorly under daytime conditions (Barr et al., 2005; Dawson et al., 2014). However, a recent YouTube video suggests it does work during daytime (www.youtube.com/watch?v=loY0mN707Og), which is also confirmed by the supplier. Glasses may be a problem for the device (Barr et al., 2005).

Acceptability
Dawson et al. (2014) report two sources that suggest low acceptability of the device.

Sustainability
The system has changed websites and its design a few times, but it still appears to be on the market.

Cost
The cost of the system is around $500 to $700, depending on the number of units purchased.

Compatibility
The device uses infrared emitters (Barr et al., 2005), which may interfere with other devices.

4 Discussion

Fatigue and distraction are important risk factors for road crashes (Dawson et al., 2014; Goldenbeld et al., 2011; SWOV, 2018; SWOV, 2019), and drivers whose jobs require them to drive are particularly affected (Charbotel et al., 2001; Driscoll et al., 2005; Harrison et al., 1993). While adequate fatigue management with sufficiently frequent breaks and sufficient time to rest is important, it will not avoid fatigue completely (Machin, 2003). Fatigue management programmes will also do little to avoid crashes due to distraction. It is for this reason that businesses that require their workers to drive (to visit clients, to bring clients to their destination, to transport goods, or to get to work) have become more and more interested in devices that may mitigate the risks of fatigue and distraction.

Until recently, most devices made use of in-vehicle sensors or physiological sensors to detect signals that may indicate driver fatigue, with a strong focus on fatigue and much less on distraction (e.g., Dawson et al., 2014; Kerick et al., 2013). With recent developments in computer vision (e.g., Sivaraman & Trivedi, 2013), and the introduction of smartphones that may lead to additional distraction (Engelberg et al., 2015), the focus of interest has shifted towards systems that detect both risk factors. The introduction of such computer visions systems, however, has also raised privacy concerns among drivers (Kustoms, 2018).

Several studies have reviewed commercially available and promising technologies to detect driver fatigue and distraction (Barr et al., 2005; Dawson et al., 2014; Hartley et al., 2000; Kerick et al., 2013; Mabry et al., 2019; NHVR, 2019), each with their specific focus and aims. Dawson et al. (2014) specifically focused on fatigue and on the scientific evidence supporting the accuracy of the devices. Kerick et al. (2013) also focused on fatigue and examined devices in a context of deployment within the army, providing an overview of general principles. Mabry et al. (2019) examined several devices in detail, including considerations such as the cost of the device, but only described a limited number of devices. Here, we have extended this work by examining a large number of devices, examining both fatigue and distraction detection, and have scored each device on a list of eight criteria: (1) validity, (2) intrusiveness, (3) availability, (4) robustness, (5) acceptability, (6) sustainability, (7) cost, and (8) compatibility (with other systems). Besides doing well on these criteria, ideally, devices should be able to detect both fatigue and distraction, and provide real-time warnings. In addition to providing an overview, the present review has also worked towards compiling a list of devices with sufficient promise for further testing in a field test.

4.1 Fitness-for-duty

Scoring the devices on the eight set criteria, without additionally requiring distraction detection and real-time monitoring, it was found that one category of devices clearly outperformed other categories. This category was that of the fitness-for-duty tests, These tests determine whether a driver is sufficiently alert to start their trip (and will therefore not provide real-time monitoring or distraction detection). Such devices have often been extensively and independently evaluated, do not interfere with driving (as they are used before driving starts), are no longer in a

development stage, work for a variety of drivers, are easily accepted by drivers, are likely to be on the market for a while, do not require extensive maintenance, are low in cost, and are compatible with other systems in the vehicle.

Despite these advantages, it would be unwise to suggest a field test that only focuses on such systems. The downside of fitness-for-duty tests is that they only focus on the start of the shift (or continuation of the trip, when used in breaks), and therefore do not detect immediate risk while driving. They also do not measure or detect distraction. While a field test should include a few fitness-for-duty tests, it should therefore also examine other devices for continuous monitoring.

4.2 EEG measurements

In terms of validity, the continuous monitoring systems that have the strongest evidence in the scientific literature are EEG systems, but the downside is that they are quite intrusive and generally rather expensive when purchased in smaller numbers. Moreover, the scientific evidence focuses in particular on whether the systems can accurately measure EEG, and less on how well the systems perform in real-time fatigue detection under real-world conditions. EEG systems measure brain waves, and when analysed in terms of their frequencies, there are two components that are particularly predictive for the onset of sleep: theta and alpha waves. Because of these clear sleep markers, EEG is often used as a baseline for the measure of fatigue when evaluating other measures (e.g., Dinges, Mallis & Maislin, 1998). A single electrode may suffice for adequate fatigue detection (Hu, 2017), avoiding the need for extensive coverage of the scalp.

Until recently, EEG recordings required the use of conductive gel between the electrodes and the skin, and often the skin needed to be prepared (thoroughly cleaned) before applying the gel and electrodes, which could cause skin irritation, particularly during long EEG recordings. Newer systems (e.g., Smart Cap, B-alert) use electrodes that can be embedded in a cap or hat and no longer need conductive gel. A field test by B-alert has suggested that such systems are acceptable for younger drivers, but may encounter some resistance from older drivers. One device (Freerlogic) suggested that EEG could be recorded from inside a headrest, but insufficient evidence could be found for such contactless EEG recordings, and therefore this system cannot be recommended. Because of the extensive validation of EEG systems, but some doubts about their acceptability to drivers, and uncertainty about how well the systems work under real-world conditions, it would be important to test at least one dry EEG system in the proposed field test. The systems show promise, but it would go too far to immediately implement them on a large scale without further testing. Suppliers of the B-alert system have indicated to have experience in field studies and would be interested in taking part, and it is therefore the recommended system.

4.3 Computer vision

While EEG systems have been extensively validated for drowsiness, fatigue and sleep monitoring, whether they can detect distraction is less clear. Computer vision systems may be better suited for this task, particularly when equipped with a camera that faces the driver (e.g., to detect the use of mobile phones, eating and drinking, or watching other parts of the scene than the road ahead). Devices that use computer vision to monitor the driver vary between relatively low-cost systems, some of which can be purchased from general stores such as Amazon and Alibaba (Stonkam, MR688, TS Monitor, F16) and more advanced systems (such as Guardian, OpGuard, Streamax and Eyesight). The business of computer vision systems appears to involve a highly competitive market, and it was often found to be difficult to obtain details about how accurate the various systems are, or how much they cost (with the exception of the Nauto system). Recent advances in computer vision, for example in face recognition (e.g., BBC News: Shead, 2019), and various scientific demonstrations of the potential of this technology (e.g., Savaş & Becerikli, 2018;

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He et al., 2017) imply that computer vision systems need to be part of a field study, despite a lack of scientific evidence of individual systems. They show promise in fatigue and distraction detection and provide real-time feedback to the driver.

Most systems have in common that they use infrared cameras, sometimes combined with an infrared light emitter. Similar equipment allows for the measurement of eye movements (combining information about pupil direction and a reflection of infrared light from the cornea of the eye), and because eye gaze direction or eyelid closure are important features to detect distraction and fatigue (Dinges et al., 1999), it is not surprising that computer vision systems use similar technology to monitor the driver. A further advantage is that infrared light systems can also be used under night-time conditions, when fatigue detection may become even more important. Besides detecting whether drivers pay attention to the road, computer vision systems can also directly detect various behaviours that suggest distraction, such as phone use, smoking, eating and drinking. In this respect, computer vision systems outperform eye tracking systems that specifically focus on eye gaze direction. Detection of smoking may be of particular importance in the oil and gas industry.

Privacy concerns are an important issue for computer vision systems that monitor the driver. Uber drivers, for example, have expressed concerns about the Nauto system that they are using. Customers in the back seat expressed feelings of being watched, and the phone detection system may be too sensitive for drivers than need to monitor their phones for future assignments (although one may argue that this may be a sign of the system doing its job well). Different companies appear to have different strategies to cope with these privacy concerns. For example, the creators of the Guardian system show a focus on educating drivers by explaining the possible benefits of camera images for the driver (e.g., to exonerate drivers in the case of a collision, and the importance of safely returning to their families at the end of their shifts). Alternatively, the Eyesight system ensures that all of the necessary processing of the video images can be performed in real-time inside the vehicle, thereby avoiding that the images need to be transferred to a server for further processing.

Computer vision systems that monitor the driver show great promise, particularly because of recent developments in technology, and their potential to monitor for both fatigue and distraction in real-time. There are, however, few scientific studies demonstrating the validity of such systems, and acceptability is a concern. For the field test, it is therefore recommended to compare (at least) three computer vision systems that monitor the driver: one lower-cost system, as a baseline for what can be expected from a lower-cost system, one system that performs all processing of the images locally (to determine whether this is feasible and yields sufficient accuracy) and one system that performs processing of the images in the cloud (to determine whether this improves accuracy of the system, and is still acceptable to drivers). For the lower-cost system, Stonkam would be recommended for having some level of support and their own website. Recommended higher cost systems are Eyesight (stand-alone processing) and Guardian (cloud-processing), as these systems appear to be ahead of other systems on the market in the development of their products (as far as this can be judged from the available materials and information).

4.4   Forward-facing cameras

As indicated, cameras facing the driver can raise privacy concerns. Such privacy issues are less of a concern for computer vision systems that use a forward-facing camera that only records the road and not the driver. On the downside, forward-facing cameras have to rely on indirect measures to detect fatigue and distraction, such as lane departures (AutoVue), near-collisions with other vehicles (Safetrack, Mobileye), or near-collisions with people (Blaxtair). While forward-facing camera systems are less intrusive because the driver is never in view, these devices will

only detect events and will not provide strong evidence of why these events happen (e.g., the driver may drift out of a lane, which could be due to either fatigue or distraction).

While systems with forward-facing cameras have already been implemented in commercially available vehicles, there appear to be few independent studies of how well such systems work (Dawson et al., 2014). To avoid that a field study would dismiss all computer vision systems, because drivers do not accept a camera looking into the cabin, it would therefore be recommended to include one computer system that only monitors the road to determine how well indirect measures detect the consequences of fatigue and distraction. The field study would demonstrate to which extent the systems predict fatigue and distraction (e.g., by detecting changes in movements of the vehicle that deviate from normal driving), whether the systems only react when a crash due to these factors is imminent. The study would also reveal how well the system works in the absence of lane markings. From the devices considered in this review, Mobileye would be the product of choice. There are concerns about the large-scale availability of the AutoVue and Safetrak systems and Blaxtair solely focuses on preventing collisions with people.

In the above, Nauto was already mentioned. It was not recommended at that point, because the system falls into the category of computer vision systems that monitor both the driver and the road. At this point, it is unclear to which extent monitoring both the driver and the road improves fatigue and distraction detection over just monitoring the driver (for distraction detection, a system that monitors the driver is likely to outperform one that just monitors the road). For the field study, it is therefore recommended to include a system that monitors both. From the systems considered (Idrive, Exeros, Nauto and Streamax), most information about the underlying principles and the cost of the system could be found for Nauto. The system was implemented in Uber taxis, providing further information on the expected acceptability of the device (suggesting this may be an issue, but it is unclear whether these concerns would mean the system would be unacceptable to drivers). One system that allows for stand-alone processing is Streamax, which could therefore be more acceptable to drivers. Moreover, Streamax analyses for both fatigue and distraction, whereas Nauto appears to focus on distraction. Streamax will be more expensive than Nauto, but is, in cost, similar to systems like Guardian and Eyesight. Streamax will also monitor the road, which will help prevent safety-critical events for which there are no clear indications of driver fatigue or distraction (e.g., microsleeps or mental distraction). For these reasons, both Nauto and Streamax are recommended for the field study.

4.5 Other systems

Depending on the scale of the field study, further systems could be considered. First, there is the extensively validated Optalert system. The current version consists of a lightweight pair of glasses and monitors both eyelid closure, and the velocity of the closing movements. Whether or not to include this system in the field study would depend on whether drivers indicate that continuously wearing a pair of glasses for fatigue detection would be acceptable. The system would not detect distraction.

Other types of systems that may be added to the field study are activity trackers that use a computational model (Readiband or Cat Smartband). These systems are limited to fatigue detection (i.e., do not detect distraction), and will not react to lapses of fatigue. They are, however, expected to make more detailed predictions of fatigue lapses than fitness-for-duty tests and fatigue models. This is because they record actual sleep patterns (instead of reported ones, as in fatigue models), and will predict fatigue (rather than simply measure it, as in fitness-for-duty tests). An important reason to add activity trackers with fatigue models is that they may be easier to accept for drivers than camera and EEG systems. Neither of the two activity trackers with fatigue models, Readiband and Cat Smartband, seems to outperform the other system.

A third type of system to consider is the Bosch or Mercedes system, which both monitor steering movements. With an adequate prediction model, these may be able to detect fatigue or distraction from changes in steering movement patterns. How susceptible these systems are, for example, to changes in steering movement patterns due to, for example, uneven road or adverse weather conditions, is unclear. There are some indications that steering movements may be a poor predictor of fatigue under real-world driving conditions (Friedrichs & Yang, 2010; McDonald et al., 2014; Sayed & Eskandarian, 2001), but there are also indications that the Bosch and Mercedes systems record additional variables (the vendor's website). Inclusion in a field study would establish whether Bosch and Mercedes have succeeded to improve their systems beyond results reported in the scientific literature. An important advantage of steering movement systems is that they are likely to be acceptable to drivers (no use of cameras or devices that need to be worn), as long as the false alarm rate is sufficiently low. The systems would, however, require adding sensors to the vehicle. There is no indication of a clear difference between the Bosch and Mercedes systems, so no clear preference for one particular system exists.

Other systems are less likely to work when used in isolation. These include systems that monitor heart rate (e.g., Bioharness, Warden, Canaria), head nodding (co-pilot, AlertMe, Safeguard), skin conductance (EDVTCS, Drover Fatigue Alarm) and isolated fatigue (e.g., CAS-5). Camera systems without computer vision (MTData, Smartdrive) do not provide real-time feedback and may serve driver education purposes only and may therefore be less relevant in the present context. Eye tracking systems are unlikely to outperform computer vision systems, which can also detect facial features, emotions, and what else is happening inside the cabin or on the road (besides measuring eye movements and eye features, such as eyelid closure and blink rate). Particularly for distraction detection, the ability to detect behaviours such as phone use, eating and drinking and smoking can be an advantage, besides detecting periods during which drivers take their eyes off the road (e.g., while talking on the phone they may still look at the road).

4.6 Recommendation

For the field test the above considerations yield the following list of devices, with specifically suggested systems in boldface:

1. Two or three fitness-for-duty tests. These systems have been evaluated extensively, are likely to be accepted by drivers, and do not interfere with driving. Because a free version is available, and the test has been validated extensively, the **psychomotor vigilance test** (PVT) is recommended to be one of these tests. It would also be recommended to include one system that makes use of a measure that is less easy to control voluntarily and takes less time to measure. Therefore, it is recommended to compare the **FIT** device (using pupil diameter) or the **OSPAT** device (object tracking) to the PVT. An important limitation of fitness-for-duty tests is that they do not detect fatigue (and distraction) in real-time.

2. A dry EEG system (Smart Cap or **B-alert**). EEG systems have been demonstrated to be accurate for fatigue and drowsiness detection. Dry EEG systems have been shown to be sufficiently accurate for EEG detection. For real-time fatigue detection with the available devices, no independent evaluations were found, but the systems show sufficient promise to be included. B-alert has experience with running a field study and is willing to share their experiences.

3. Two or three computer vision systems that use a camera facing the driver. These systems show potential in detecting not only fatigue and drivers taking their eyes off the road, but also detecting possible other causes of distraction, such as phone use or eating and drinking. Independent evidence that these systems work, however, is sparse. Here, it may be important to compare one or two higher-cost systems (e.g., **Eyesight, Guardian**) with a lower-cost

device (e.g., **Stonkam,** MR688, TS DFM, F16) to determine whether the difference in cost relates to the accuracy of the device. Comparing Eyesight (in-vehicle processing of the recordings) with Guardian (cloud-processing of the recordings) will inform whether local image processing will enhance acceptability of the device.

4. One system that uses a forward-facing camera only. Computer vision systems are the only systems that show sufficient promise in detecting distraction (besides detecting fatigue). Systems with a camera facing the driver, however, may suffer from acceptability issues, but it is unclear how extensive such issues are. To avoid a situation in which it has to be concluded that none of the computer vision systems is sufficiently acceptable, it is therefore advised to include one system that only monitors the road (which is less likely to raise a privacy concern). Here, **Mobileye** may be a good candidate, because of its extensive development of the relevant hardware, but also because of an apparent lack of other big players in the market. From the other forward facing camera systems, Blaxtair focuses on collisions with people only. Availability of the Safetrak and AutoVue systems is uncertain.

5. Two systems that combine a forward facing camera and a camera facing the driver. It is unclear whether systems that monitor both the road and the driver will outperform those that only monitor the driver (they are likely to outperform systems that only monitor the road for distraction detection), but situations in which a forward facing camera could help are during microsleeps and mental distraction. Here, **Nauto** and **Streamax** are the two systems to consider first. Nauto has already been deployed in Uber taxis, it is relatively low-cost (no cost information available for the other devices) and well-documented on the vendor's website. Streamax can operate without sending images to fleet management, which will make it more acceptable to drivers.

The following three types of systems may be added, depending on the number of devices compared in the field study:

6. The **Optalert** device. This device has been evaluated extensively and has demonstrated good performance in fatigue detection. A possible concern is that not all drivers may accept wearing glasses full-time. The device only measures fatigue.

7. One activity tracker (e.g., **Readiband**, Smart Band). Younger drivers are likely to accept such devices. Although they do not continuously monitor fatigue, they may be better at predicting future fatigue than mathematical models or fitness-for-duty tests alone.

8. The **Bosch** or Mercedes system. While steering wheel movements were relatively poor at predicting fatigue under real-world conditions, this system gathers additional information that may influence steering wheel movements, such as information about weather conditions, and may therefore perform better than systems that only use steering wheel information. The Bosch system seems to be available to be placed in different types of vehicles.

Distraction detection

The above list contains systems that can detect fatigue and systems that can detect both fatigue and distraction. If the aim is to find a system that can monitor both fatigue and distraction, only the computer systems that monitor the driver are likely to suffice. Other signals, such as steering movements, EEG, and distance to the vehicle ahead may provide some clues of driver distraction, but may not be sufficiently reliable, or may not be able to warn the driver on time. Direct detection of off-road gaze behaviour, mobile phone use, and eating and drinking from images is much more likely to lead to successful detection of distraction. Such analysis of driver images is also much more likely to result in timely warnings. From the above list, the **Eyesight**, **Guardian,** **Streamax** and **Nauto** systems would all provide this information.

Past recommendations

In comparison with past reviews, the present review has led to a few different recommendations, possibly because of the focus on distraction detection in addition to fatigue monitoring. A further reason could be that new systems have been brought to market and others appear to have been abandoned. Compared to Kerick et al. (2013), the only device that overlaps is the Optalert device. In the present review, it was recommended only in a second step, because of possible concerns of drivers having to wear glasses full-time. The current and previous review by Mabry et al. (2019) both recommend a dry EEG system, but the two reviews differ in the exact device recommended (the present review recommends b-Alert, while Mabry et al. recommend Smart Cap). The present review and Mabry at al. also both recommend the Guardian system, and the Optalert system. Mabry et al. also list a series of systems as 'promising', but none of these systems made it to the present recommendation list. A possible reason is that the current review also had distraction detection as a criterion and considered a broader range of criteria. In comparison to Dawson et al. (2014), there was an overlap for the PVT, FIT, OSPAT, Guardian, and B-alert systems. Safetrak would have made it to the current list, if there had been more indications that the system is still available. Differences in recommendations such as these were an important reason for the levels of detail of the current report. Whether a system is suitable will depend on user criteria. Simply scoring each device for validity would not have allowed the use of the overview for different users and different contexts.

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Appendix: Other devices and systems

This appendix provides an overview of the devices from the original list for which insufficient information could be obtained, or for which the aim of the device appears to be something else than fatigue or distraction detection. This appendix also describes some devices that are similar to others already included in the review, but that do not seem to outperform these other systems.

Bioharness

Bioharness (available from www.biopac.com and www.zephyranywhere.com) consists of an array of sensors worn on the body that measure heart rate (Figure A.1b). The validity of the device was laid out in various peer reviewed journal articles (Johns & Hocking, 2015; Johnstone et al., 2012a; 2012b; Kim et al., 2013; Nazari et al., 2019; Nepi et al., 2016). In a review of 10 studies of the system, Nazari et al. (2019) found evidence of good to excellent reliability of heart rate measurements by the system. Individual studies included De Vries et al. (2013), who suggested that while the individual signals measured by the systems (e.g., heart rate, breathing rate) were not always predictive of physical stress on the body, the combination of signals was well able to distinguish between low and high stress periods during a shift (tested in firemen and professional football players).

The device currently does not provide alerts for fatigue (Mabry et al., 2019). Its main purpose is to measure and record a range of physiological signals, which it does reliably, as evidenced by the literature (Nazari et al., 2019). Mabry et al. (2019) label the device as 'promising', but are the only review to mention the device.

Infinity labs

Infinity labs is a start-up in Breda, The Netherlands, using VR and eye tracking. There appears to be no website and the only link to the company appears to be the CEO on LinkedIn. A contact request for more information did not produce results.

Eye-Com

Eye-com is mentioned by Dawson et al. (2014) and NHVR (2019). The web-address for the company is for sale (eyecomcorp.com) and the last Tweet by the company on Twitter was posted in 2012.

Zentrela

The Zentrala system (www.zentrela.com) focuses on detection of tetrahydrocannabinol (THC), the psychoactive substance of cannabis, and uses a combination of a headband and a smartphone application. The website does not indicate that the system can also be used for

detecting fatigue. Pictures of the device suggest that it may not be suitable to be worn for prolonged periods of time.

Figure A.1. a) Guard-Ex, b) Bioharness, c) NoNap.
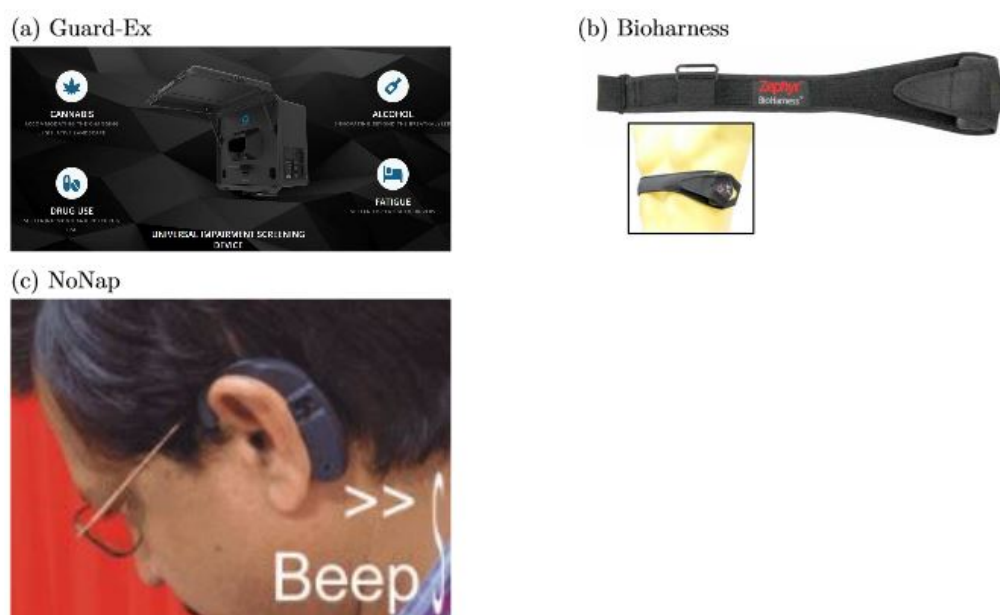
Innovation York

The product by Innovation York is set up to detect THC faster and in lower concentrations in human saliva than currently available systems. It was developed by Nima Tabatabaei at York University (York University, 2019) and makes use of the thermal signature of gold nanoparticles attached to THC molecules. The work was supported by a $50,000 grant from York University and a subsequent grant of $125,000 from the NSERC / CRSNG. The product seems to be in the development stage and is specifically focused on THC detection and not on fatigue or distraction.

Micro-Nod Detection System

The Micro-Nod system was described by Hartley et al. (2000), Dawson et al. (2014), NHVR (2019) and in Meireles & Dantas (2019). It detects fatigue on the basis of head nodding, and may therefore not pick up microsleeps that occur without nodding. Hartley et al. (2000) described the system as still in the development stage. Dawson et al. (2014) indicated that no validation had been performed on the system. No recent information could be found on the system, suggesting that it either never left the development stage, or that the system was discontinued after an initial start-up.

Stay awake

This system was mentioned by Dawson et al. (2014) (suggesting no tests showing its validity), NHVR (2019), and was described by Mabry et al. (2019). It is a wearable device that can be worn over the ear, which measures head position and produces a high-pitched sound when head nodding is detected (Mabry et al., 2019). The website (stayawakedevice.com) no longer seems to be available. Mabry et al. (2019) rated the device as 'unlikely to be used in future'.

Guard-Ex

Figure A.1a shows the Guard-Ex device. The website of the development team (www.guard-ex.net) provides little information about what the device does and how it works. As indicated in Figure A.1a, the device has been developed to measure drug use, alcohol use and fatigue. A YouTube video starring the development team suggests that it consists of headgear that measures pupil diameter, heart rate, muscle tone and EEG signals. The website suggests that these signals are fed into a machine learning algorithm to decide whether the driver is fit to drive. As such the device appears to be a fitness-to-work instrument. The device still seems to be in the development stage.

Project 'well being'

This is a project testing the use of a heart rate variability monitor (3DAYME) for measuring how well workers recover from physical and mental stress, and for measuring their sleep quality. An initial pilot with seven participants has been conducted. Now a study with 30 participants is being set up. The use of the trial for online fatigue detection in drivers is less clear.

TravelMate

The TravelMate device was listed in reviews by Dawson et al. (2014), Hartley et al. (2000) and NHVR (2019). The device was said to make use of head nodding behaviour to detect fatigue (Dawson et al., 2014; Hartley et al., 2000) and had not been validated in field studies (Dawson et al., 2014). A Google search for 'TravelMate' in combination with 'fatigue' gave information about laptops only, and it therefore appears that the device has not been brought to market, and/or is no longer available for purchase.

Dozer's alarm

The Dozer's alarm was listed by two reviews (Dawson et al., 2014; NHVR, 2019), which both indicated that the system makes use of head nodding to detect fatigue. Dawson et al. (2014) indicated that the system had undergone some validation (but with little evidence that it worked), and that the system was not yet commercially available at the time of writing. A Google search did not come up with a device under the same name that uses head nodding for fatigue detection, and it therefore appears that the system has not been made available commercially.

AR7000 Flagship Mixed Signal Platform

The AR7000 Flagship Mixed Signal Platform was described in Kerick et al. (2013) as a multi-sensor (e.g., ECG, EOG, EEG) system. On the website (www.atlas-arl.com), a case study describes a wristwatch-like device that analyses EMG (wrist-muscle tension) of the driver's steering hand. A Canadian study is mentioned (without reference) for the scientific validity of the device. The e-mail address on the website no longer appears to work. Looking for the CEO, a new website was found (www.atlasensebiomed.com), but the devices listed on this website appear to be focusing on the medical domain (e.g., Parkinson's, dehydration, hypothermia, or sleep disorders).

LUCI

The LUCI system was developed in the context of a partnership between Six Safety Systems and one of the leading eye tracker developers Tobii. Mabry et al. (2019) described the system as a desk-mounted system that measures eye movements using infrared sensors. Eye movement measurements are then analysed for indicators of fatigue and distraction. Visual and auditory

signals are first given to the driver only, but subsequently also to the fleet manager if they become too frequent. Signals are processed real-time, so no video images are stored or transmitted to the cloud. Mabry et al. (2019) listed the system as promising. The website of Six Safety systems, however, no longer seems to work. Other pages referring to the collaboration between Six Safety Systems and Tobii seem to date back to 2012, when the collaboration was formed. It is therefore unclear whether the system has been brought to market, or is still available for purchase.

ASL

ASL is a company producing eye trackers for research. It was mentioned in the context of fatigue by Barr et al. (2005), but there do not seem to be current extensions of the system for automatic fatigue detection. The original website (http://www.asleyetracking.com/) no longer appears to work, but an alternative website is available at http://host.web-printdesign.com/asl/, suggesting the company is still in business.

Sleep Watch Micro II

The sleep watch described by Kerick et al. (2013) no longer seems to be on the market (the website pcdsleepwatch.com does not respond). A search for Sleep Watch provides a newer watch (www.thesleepwatch.com), which measures sleep duration and sleep stages, so that users can be woken up during light sleep. This latter device costs $89.99 or $149.99.

SMI eye trackers

Kerick et al. (2013) and Barr et al. (2005) both referred to the SMI eye tracking systems. SensoMotoric Instruments was one of the leading companies in eye tracking technology, until it was taken over by Apple in 2017 (Hartzbech, 2017). As a consequence of the takeover, owners of SMI eye trackers stopped receiving support and updates for their systems. One of the systems provided by SMI were the SMI eye tracking glasses, that could produce user-centred videos with a superimposed cursor indicating the gaze direction of the user. Alsibai & Manap (2016) referred to SMI Insight, as a system that detects driver fatigue, but no further information on this system was found, possibly because of the take-over by Apple.

TravelMate

Dawson et al. (2014) and NHVR (2019) both referred to the TravelMate system, a continuous monitoring system still in the development stage, according to Dawson et al. (2014). A Google search for TravelMate or TravelMate and fatigue does not lead to a system that detects driver fatigue(instead a matching website for travellers and a laptop were found).

TravAlert

Hartley et al. (2000) described the TravAlert system as a device that monitors steering behaviour and produces a loud sound if steering behaviour is suggestive of fatigue. Ji, Lan & Looney (2006) referred to the description by Hartley et al. (2000), and provided the address of a website (www.travalert.com), which no longer appears to operate. May & Baldwin (2009) also referred to Hartley et al. (2000) and also put the system in the category of steering wheel movement monitors.

RoadGuard

The RoadGuard system was tested by Haworth & Vulcan (1991). The device was activated when the driver selected the top gear. After a variable interval a red light switched on, which had to be deactivated by the driver with a switch on the steering wheel or foot pedal. The authors concluded that the system could detect the onset of fatigue, but did not allow the driver to drive for longer and did not prevent deterioration in performance due to fatigue. Dawson et al. (2014) listed the device as having little evidence and also indicated that the same study found that users were annoyed by the system. The device can no longer be found with a Google Search, and therefore does not seem to be commercially available.

Senseye Risk Management System

Senseye (senseye.co) provides two systems: (1) a target learning system and (2) operational risk management (Figure A.2a). The second of these two systems is designed to measure fatigue. It consists of an eye movement test (Figure A.2b), making use of an eye tracker (Figure A.2c), taken before a shift to determine whether the worker is fit to work. Contact was sought with the supplier to obtain more information about the cost of the system, and the equipment involved, but no information was obtained.

Figure A.2. Senseye Risk Management System. Images retrieved from Lloyd's Register (2019) and Foster (2019).
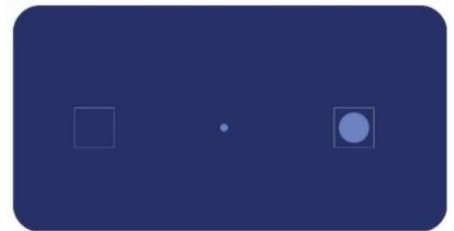
OCPT

The OCPT (online continuous performance test) tests sustained attention and vigilance in a 19-minute online test (Dawson et al., 2014). There are various studies that confirmed the validity of the test to measure sleep deprivation. One study showed higher rates of omission errors following nights with 4 hours of sleep compared to nights with 8 hours of sleep (Sadeh, Dan & Bar-Haim, 2011), but no effects on reaction times. Higher rates of omission and commission errors were also found for interrupted sleep ('Induced night-wakings', Kahn et al., 2014), while this study also found higher commission errors for 4 hours of sleep. A comparison between test performance in the lab and at home suggested acceptable reliability of the home test in young adults (Raz et al., 2014). The same study also found higher rates of omission and commission errors and higher reaction time variability in young people with attention deficit hyperactivity disorder (Raz et al., 2014). The test was also found to work in children, both at home and in a lab setting, and also here significant differences between ADHD and control participants were found

(Bart, Raz & Dan, 2014). The link to the test in Dawson et al. (2014) no longer works, and no online test could be found after searching for either OCPT or 'online continuous performance test', suggesting that the test is no longer available. The duration of the test (19 minutes) would have rendered the test an unlikely competitor to other tests that only take minutes(e.g., FIT, OSPAT).

NoNap

The NoNap (Figure A.1c) device (www.thenonap.com) is similar to the AlertMe device. The device is to be placed around the driver's left ear and will beep or vibrate as soon as head nodding consistent with the onset of sleep is detected. The default angle for nodding movements is 15 to 20 degrees, but this can be set. The device is powered by a battery. The device is said to have been tested by Electronics and Quality Development Centre of the government of India (www.thenonap.com). The device costs 350 Indian Rupies (around $5). A list of 132 users is provided on the website, including names such as Express global logistics and Touch wood industries. No validation studies could be found (see also Dawson et al., 2014). Mabry et al. (2019) put a slightly higher price tag to the device ($20) and listed it as 'unvalidated'.

Muirhead Fatigue Warning System

The Muirhead Fatigue Warning System produces a visual warning signal to test driver attention (Figure A.3a). It will then produce an auditory signal until the driver presses the reset switch. The device was mentioned by Kerick et al. (2013) and Edwards et al. (2007), but no validation studies were found.

Figure A.3. a) Muirhead, b) iMotions, c) RoadHound. d) Meitrack.

iMotions

The iMotions software (imotions.com/platform/) is described by Lupova (n.d.) as a platform for combining and processing facial expressions, eye movements, brain activity, heartbeat, galvanic skin response, EMG and questionnaire data (Figure A.3b). Lupova (n.d.) indicates that the software can be used for fatigue detection, but that online monitoring is not yet possible.

Blaxtair

The Blaxtair system (Arcure group; blaxtair.com) consists of two small cameras (sampling the environment at 8fps) placed on the front of the vehicle (Figure A.4a). Using computer vision algorithms, humans are detected in the recorded image, and a warning signal (visual and sound) is provided when the vehicle is approaching too closely. This system does not monitor fatigue or distraction, but instead aims to prevent collisions with pedestrians that may be the result of fatigue or distraction (or other factors).

The Blaxtair system was specifically designed for use in heavy duty circumstances, such as building sites. In such circumstances, there are reasons to specifically focus on pedestrian detection, because hitting a person with a heavy vehicle, even at low speeds, is likely to cause substantial harm to the pedestrian. Because of the relatively low speeds at which heavy vehicles on building sites operate, the system needs to focus on the area near the system using a broad field of view (Bui et al., 2013). While the data can be downloaded, they are not continuously transmitted to the web.

Several articles and conference proceedings in the scientific literature mention the Blaxtair system (Bui et al., 2013; Fremont et al., 2016; Lang & Günthner, 2017; Salhi et al., 2019). The article by Bui et al. (2013) focuses on improving the detection algorithm, but does not specifically test the Blaxtair system. Similarly, Fremont et al. (2016) focus on a comparison of different algorithms under various conditions of image distortions, investigating the robustness of the system, and generally conclude the results are promising in terms of both processing speed and performance. The user manual lists examples of where the system fails (see Figure A.4c), also including false positives for gas cylinders, poles, coat hangers, bushes and life size pictures of people. The manual also indicates that the localisation accuracy may vary from up to 30cm between 1 and 3 meters, and up to 50cm between 3 and 5 meters. The alarm is said to sound between 200 and 300ms after a pedestrian has been detected. The algorithms have been tested for image distortions mimicking different weather and lighting conditions and appear to be reasonably robust (Fremont et al., 2016). Humans that are on the floor or bent over may not be detected (Figure A.4).

Figure A.4.mages of the Blaxtair system.

RoadHound Distracted Driving Deterrent

The RoadHound Distracted Driving Electronic Road Sign Trailer Alert & Deterrent (https://www.bvsystems.com/product/roadhound-distracted-driving-alert-with-trailer/) is a device to be placed next to the road. It detects distraction in passing drivers and gives a warning signal (Figure A.3c). How the device exactly works is unclear. The device appears to serve mostly as a general warning to drivers to the risks of distracted driving.

Meitrack Driver Fatigue Monitor

The Meitrack driver fatigue monitor (Figure A.3d) uses a camera to detect whether the driver is drowsy, distracted, absent-minded, smoking, using the phone, or yawning, and it supplies visible and audible warning signals. It is similar to the F16 system.

StradVision

StradVision is a computer vision hardware (Figure A.5a) and software solution (Figure A.5b,c) that can be used for a variety of computer vision tasks, including forward collision warnings, pedestrian and cycling warnings, blind spot detection, and lane departure warning (Figure A.5d). The system is still in the start-up phase and investor funding is being sought.

FAID

The Fatigue Audit Inter Dyne model (FAID; https://www.interdynamics.com/fatigue-risk-management-solutions/fatigue-riskmanagement-products/) is an extensively validated fatigue model (Darwent et al., 2015; Dawson et al., 2017, 2011; Paradowski & Fletcher, 2004; Roach et al., 2006; 2004). It is based on the two-process model, assuming a process S (sleep-wake) and a process C (cyclical, sleep-wake independent) predicting fatigue from shift schedules (Dawson et al., 2011). It uses the start and end time of the shift as input and predicts a work-related fatigue score. It is often used as a decision-support tool for managing fatigue-related risk (Dawson et al.,

2011). It is one of the devices listed in the review by Kerick et al. (2013). A similar model, CAS-5, was described in the general review.

(a) Hardware
(b) Internal sensor
(c) External sensor
(d) Applications
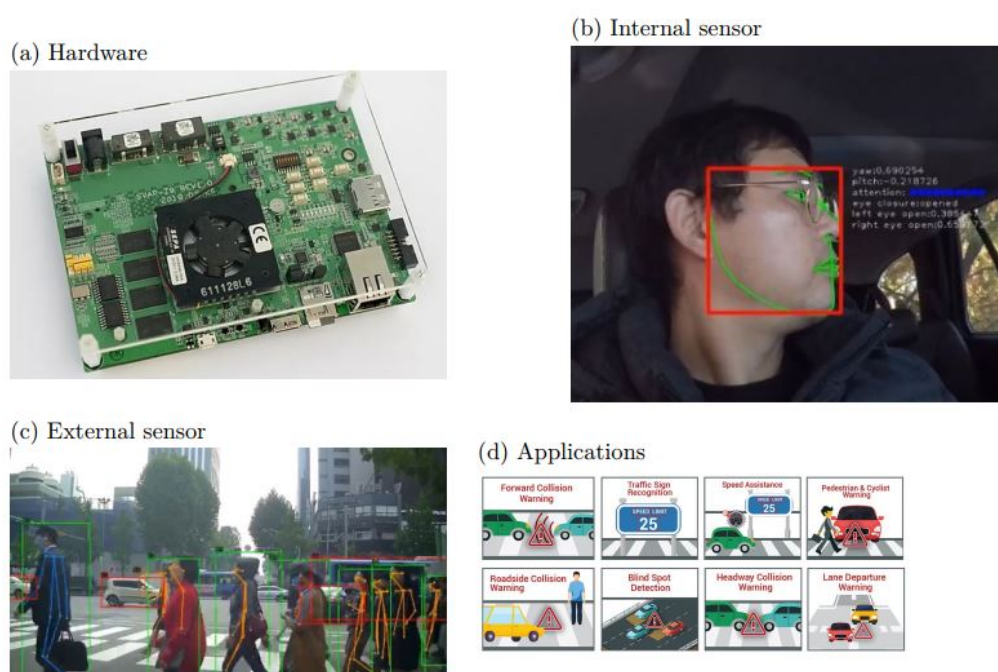
CarVi

CarVi (getcarvi.com/carvi-technology/) is a system using computer vision to analyse the images of a forward facing camera for lane departures and near-collisions with the forward vehicle. It focuses on autonomous vehicles, and it is unclear whether the system can be used in non-autonomous vehicles. A dashcam (Figure A.6a) allows for the recording of images from the vehicle for insurance purposes. A website indicates that obstacle detection is performed with a 99.5% accuracy, and that the device is 'affordable' (Peverelli & De Feniks, 2017). Lupova (n.d.) suggests the system could help drivers improve their driving.

MB fatigue calculator

The MB fatigue calculator (www.australianimporters.com/company-details.php/mbsolutions-9889.php) is a tool based on an algorithm by Drew Dawson that assesses and forecasts fatigue both for work and non-work fatigue. It is available as a handheld unit or a phone app. The link on the website (www.fatiguecalculator.com.au) no longer works, so it is unclear whether the device is still available.

Safety Scope

The device called 'Safety Scope' was described in the review by Dawson et al. (2014) as a system that conducts a fitness-for-duty test using pupil and eye movement responses to stimuli. One study tested the system in a driving simulator and found that very sleepy participants were more likely to fail the test (Heitmann et al., 2001). The device was also mentioned by Williamson & Chamberlain (2005), who also referred to Heitmann et al. (2001) for more information. The website for the device listed in Dawson et al. (2014) is no longer available, and a Google search did not yield a different domain for the product.

(a) CarVi (b) Sentinel (c) Smartwear (d) Sleeptracker
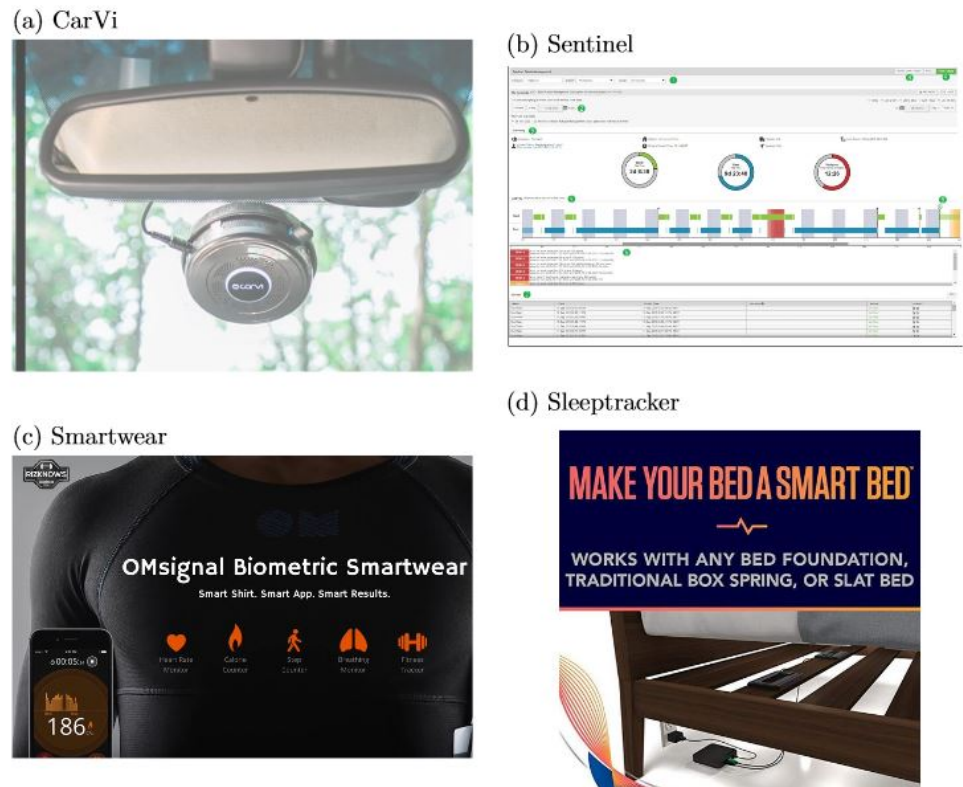
Sentinel

Sentinel (transtech.atlassian.net/wiki/spaces/TKB/pages/2654248/Sentinel) is software to plan schedules of drivers within a fleet, taking into account driving and resting times (Figure A.6b). The website provides few details about whether the system uses a fatigue model, how much the software would cost, or how accurate predictions are. No validation studies were found in Google Scholar, where searching was made difficult because of many entries about sentinel nodes and alarm fatigue.

Fatigue Meter

The Pulsar Informatics fatigue meter makes use of a computational model (McCauley et al., 2013) of the effects of sleep and sleep loss on performance. The website suggests the model is a two-process model, taking into account the homeostatic process and the circadian process, but also taking into account circadian misalignment (due to crossing time zones). References to the paper describing the model mostly include studies on fatigue modelling in pilots, where time zone influences are more likely to occur than in truck drivers. How the model compares to other computational models (Mallis et al., 2004) is not immediately clear.

ARRB Pro-Active Fatigue Management System

The ARRB fatigue management system is described by (Mabbott, 2003) as a device that measures reaction times to stimuli. The device aims to measure fitness-for-duty throughout the shift by asking workers to respond to visual and auditory stimuli at random intervals. Whether the device has been brought to market is unclear, but it no longer appears to be available.

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OMSignal SmartWear

OMSignal SmartWear is a fitness tracker that is fitted inside a t-shirt or bra and communicates with a smartphone app (Figure A.6c). It can measure heart rate, calories burnt, number of steps taken, breathing rate, and it tracks fitness. Online discussions of the product mostly took place around the time it was launched (2014). It no longer seems to be available or used. There does not seem to be a specific application to detect fatigue, other than that as a consequence of exercise. Upon its launch, the product was said to cost around $100. The idea of smart clothing that can measure heart rate and ECG has not yet been abandoned (Sanyal, 2019), and possibly future systems may be developed that will allow for fatigue detection with such clothing.

GreenRoad Drive

The GreenRoad Drive is available for free from the Apple App store (GreenRoad, 2013) and the Google play store (GreenRoad, 2019). It was reviewed by 12 users on the Apple App store (giving the app an average of two stars out of five), and by 323 users on the Google play store (three stars out of five). getapp.com, in contrast, shows three reviews who all give the app top marks, but charges $12/month.

The images of the app suggest that the app provides feedback on events, such as braking. Using such events, the app will indicate how safely a fleet is driving and will allow for detailed analysis of events, ranking of drivers, providing notifications, and awarding gifts (Figure A.7). The app will not warn drivers for fatigue or distraction, but instead uses events to educate drivers to drive more safely.

The app can detect 150 different driving manoeuvres related to safety and fuel efficiency. It provides in-vehicle alerts for risky actions. After the trip, summaries can be viewed to avoid repeating driving mistakes. Drivers within a fleet can compete to reduce their safety events compared to their peers. Safety managers can live track their fleet and driving behaviour and award their best drivers gifts (GreenRoad, 2019).

The FAQ on the website (greenroad.com/faqs/) indicates that the app makes use of the accelerometer and GPS data, and measures risky driving behaviour from the forces on the vehicle during events. Feedback is given, taking into account properties of the vehicle. The FAQ indicates that the 150 detected driving manoeuvres include speeding, cornering, lane handling, braking, acceleration and idling. A green-yellow-red colour scheme is used to provide visual feedback. The FAQ also suggests that the app can reduce fuel consumption by 15-30%, crash-related expenses by 50-70% (repairs and lower insurance premiums) and vehicle wear and tear by 10%.

Google Scholar provides three articles for 'GreenRoad app' (Calderwood & Ackerman, 2019; Júnior et al., 2017; Levi-Bliech et al., 2019). Calderwood & Ackerman (2019) tracked the driving behaviour of 50 participants during a two-week study period using the GreenRoad app. Additionally, participants completed daily surveys in return for $65 for completing all stages of the study. The results suggested that employees were driving more safely when they encountered more challenges at work. Events that led to negative emotions led to less safe driving. For information about the reliability of the app, Calderwood & Ackerman (2019) referred to Musicant, Bar-Gera & Schechtman (2014) and Musicant, Bar-Gera & Schechtman (2010), but a different app (RefuelMe, developed by StreetOwl) appears to have been tested in these studies.

While many users have rated the system, written feedback is sparse (there is one such feedback for Android, and three for iOS). For Android the reviewer indicates that a different system (GreenRoad Central) worked better for tracking a vehicle. The iOS reviewers indicate that the app is not very accurate (e.g., when measuring velocity or braking speed, and when determining the

speed limit). The reviewers on getapp.com rate the app highly, but also list some cons, including that the GPS tracking is not always up to date and that the customer service could be better.

Figure A.7. Images showing the GreenRoad Drive app. Images taken from the Google play store website (GreenRoad, 2019).
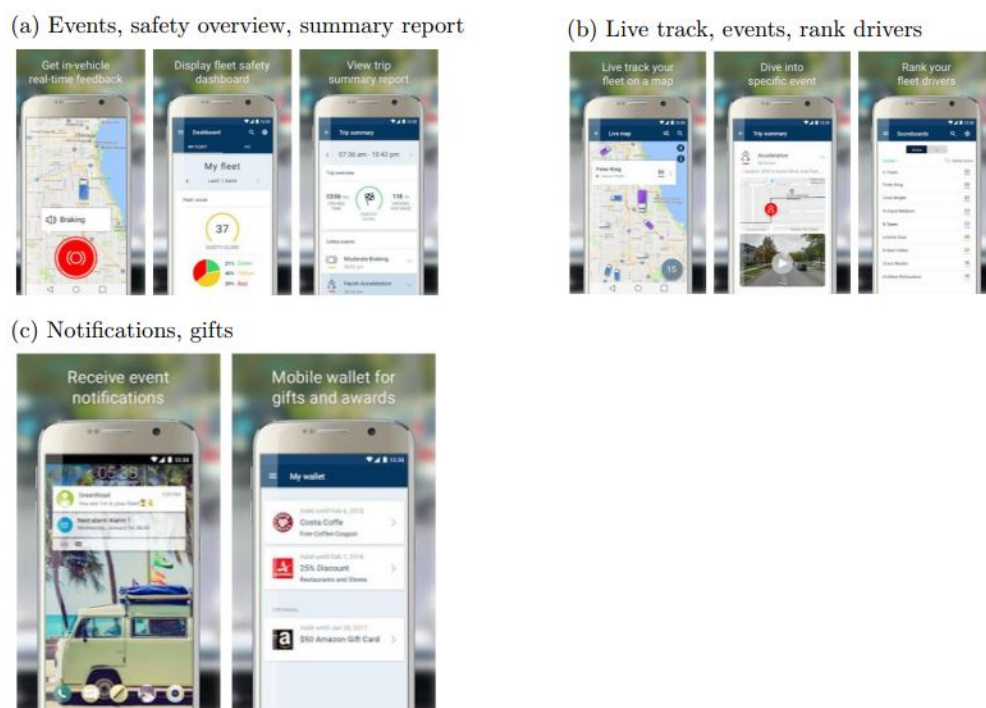
SleepWatch App

The SleepWatch app (sleepwatchapp.com) is a combination of a smartwatch (Apple Watch) and a smartphone (iPhone) app to monitor sleep patterns. SleepWatch provides the software that runs on Apple hardware. The device can monitor for sleep rhythms, sleep disruptions, time needed to fall asleep, heart rate dips, sleeping heart rate, and sleeping heart rate variability, and provides predictions for sleepiness in the morning and afternoon. There are two versions: a free version and a premium version (costing $2.99 a month). The free version was rated 4.6 out of 5 stars by 142.8K users on the Apple app store. While the device may help get a better night's rest, and may serve as a fitness-for-duty test, it will not monitor for fatigue (or distraction) while driving.

System for Aircrew Fatigue Evaluation (SAFE)

The System for Aircrew Fatigue Evaluation (SAFE) is a mathematical model to predict, from sleep patterns, when someone is likely to become fatigued (in 15-minute intervals, Kerick et al., 2013). It is mainly applied in the aviation industry, where jet lags influence sleepiness in pilots and crew. Its main purpose is scheduling shifts of airline crew. A comparison of various mathematical models found little difference in performance (Dawson et al., 2011).

Sleeptracker

Sleeptracker (www.sleeptracker.com) is a device that can be placed inside the bed (Figure A.6d) to measure the quality of sleep. The device is sold on Amazon.com for $187.50. The 131 ratings on Amazon.com rate the product at four out of five stars. One reviewer indicates that the device measures heart rate, breathing rate, and getting in and out of bed. The same reviewer indicates that the device will classify sleep into light sleep, deep sleep, and REM sleep, and will send e-mails with advice on how to improve sleep quality. Several reviewers mention that the device

does not seem to detect when you are awake in bed. The device may work as a fitness-for-duty test, but not as a continuous monitor for fatigue and distraction. Because many devices are called sleep trackers, it is difficult to find articles referring to this particular device. At least one conference proceeding appears to mention the device (Schmidt, Shirazi & Van Laerhoven, 2012), as well as one review paper (Kerick et al., 2013), although the latter talks about a wristwatch.

DriveFit

Drive Fit (http://www.drivefitsolutions.com.au/services.htm) provides a range of services, including workshops and seminars, consulting, fatigue compliance training, and driving assessments. They do not offer fatigue or distraction detection devices, but instead focus on education and training.

Prevent crashes
Reduce injuries
Save lives