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Fatigue in transport: a review of exposure, risks, checks and controls*

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ABSTRACT

Human fatigue continues to threaten safe transport. There are claims that employers of operators should do more to mitigate the risks, and several regulators are promoting fatigue-risk management in the context of safety management systems (SMS). The current paper reviews fatigue-related risk and exposure factors and control measures for operators of land- and sea-based transport forms. Our review identifies 13 types of measures for the monitoring or control of fatigue risks: optimal staffing; optimal schedule design; optimisation of breaks/naps; monitoring of actual hours worked; optimisation of work content; monitoring and feedback of actual sleep; health screening and treatment; promotion of recovery from work; fitness-for-duty testing; monitoring of fatigue symptoms while operating; control of fatigue while operating; performance monitoring and assistance; and fatigue-proofing. We also identify two systemic measures needed to anchor risk mitigation in SMS: organisational learning and training/other. By structuring monitoring and control measures along Dawson and McCulloch's [Managing fatigue: It's about sleep. *Sleep Medicine Reviews*, 9(5), 365–380] fatigue-risk trajectory, a framework is obtained that acts as a guide for fatigue-risk management by transport employers. To inform transport managers further, evaluations are needed of the effectiveness of individual control measures as well as whole fatigue-risk management interventions.

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Introduction

Transport operator fatigue is a threat to safe transport by road, rail, sea and air, and has environmental, economic and health costs (Akhtar & Utne, 2015a, 2015b; Bidasca & Townsend, 2014; Caldwell, Caldwell, & Schmidt, 2008; Dorrian, Hussey, & Dawson, 2007; Williamson & Friswell, 2013a, 2013b). It is not a new problem, but there are claims that more should be done to tackle operator fatigue, not least by organisations which are

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well placed to manage and influence the fatigue of their employees (Phillips & Sagberg, 2010). In a parallel development, authorities have encouraged transport companies to implement safety management systems (SMS), which are evidence-based risk assessment and mitigation procedures anchored in company policies, roles and documents, and supported by management commitment to safety, a positive safety culture and data-driven continuous learning (Lerman et al., 2012).

Given these two developments, it would be desirable to stimulate transport organisations to manage fatigue as a risk in the context of SMS. To help do this, factors determining fatigue-related exposures and risks in transport should be presented along with the measures that can contain them, in a way that is consistent with risk management. In line with this thinking, a recent literature survey study reviewed fatigue "countermeasures" and structured them along Dawson and McCulloch's (2005) fatigue-risk trajectory (Phillips, 2016). The current paper presents a concise account of this study to a wider audience, and adds value in two ways. Firstly, we distinguish more clearly between exposure and risk factors, on the one side, and monitoring and control measures, on the other. This is important since it is more consistent with risk management practice and will increase coherence for researchers and managers who need to mitigate transport operator fatigue. Secondly, the present article considers the pros, cons and effectiveness of the fatigue measures, and indicates the "weight of evidence" for each type of risk factor or measure considered. It should interest researchers and practitioners in developed countries, who aim to improve the management of fatigue in employee operators of vehicles or vessels. The approach may also be of interest to authorities and action groups aiming to reduce the problem of fatigue in private drivers.

In the rest of this introduction, we explain what we mean by *fatigue*, why it still needs to be addressed to improve transport safety and how this might be done effectively by managing fatigue along a risk hierarchy.

What is fatigue?

There are varying definitions of fatigue, but several share the idea that it is a state caused by exertion (Phillips, 2015). A typical definition of fatigue is as the body–mind response to sleep loss or prolonged physical or mental exertion. In transport operators, the extent and effects of sleep loss, exertion and consequent fatigue are influenced by individual, job and environmental factors (Williamson & Friswell, 2013a, 2013b). Fatigue can manifest itself physiologically, cognitively or emotionally, and can be detected by observation of behaviour, by self-reports of sleepiness or by cognitive or physiological measurements (Christodoulou, 2012).

Sleep drives are well described by the 2-process model of sleep regulation (Borbély, 1982), in which sleep onset is predicted by the function of (i) homeostatic drives (drive towards sleep increases with time since last slept) and (ii) circadian drives (sinusoidal function that programmes sleep to occur during the night and to stop during the day). We consider that fatigue differs from the sleepiness that results from normal sleep drives, since the latter arise independently of exertion (Åkerstedt, Folkard, & Portin, 2004). Nonetheless, sleep drives are an important aspect of fatigue, since one becomes fatigued whenever one is motivated to work or *exert* oneself when one would otherwise be driven to sleep (e.g. after not having slept for a long time or through the circadian nadir). Authors have highlighted the importance for control of distinguishing between fatigue caused by task- and sleep-related exertion (e.g. May & Baldwin, 2009), and whether task-related exertion is active or passive in nature (Hancock, Desmond, & Matthews, 2012). In the rest of this paper, *fatigue* is used to denote both sleep- and both forms of task-related fatigue.

Need to address fatigue in transport

Fatigue has been shown to affect the cognitive and behavioural safety performance of transport operators (Horne, 2012; Lim & Dinges, 2010), and has been linked to safety outcomes in general workers (Williamson et al., 2011). It is also implied in the links found between shift work and long-term health disorders (Costa, 2010; Lie et al., 2014). For organisations, fatigue-related outcomes can cause increased sickness absence, employee turnover and poorer economic outcomes in terms of maintenance costs or insurance claims (Bidasca & Townsend, 2014).

There are several reasons to believe that fatigue remains a hazard for transport operators. Seafarers face increasing workloads and staffing cuts (Smith, Allen, & Wadsworth, 2008), truck drivers face increasing competition and delivery pressures (Enehaug & Gamperiene, 2010) and bus drivers face increasing competition while continuing to meet demands of punctuality, safety and customer service (Anund, Fors, Kecklund, van Leeuwen, & Åkersted, 2015; Kompier, 1996). Recent times have also seen partial automation of operator tasks, potentially increasing the extent of passive task-related fatigue (May & Baldwin, 2009). Moreover, substantial shares of transport accidents are still caused by fatigue (Phillips, Nævestad, & Bjørnskau, 2015; Williamson et al., 2011). Even when the operator task is fully automated, fatigue in maintenance personnel, control room staff and others will continue to threaten safe transport operations.

Mitigating fatigue through risk management

Transport operator fatigue has traditionally been managed by rules prescribing clear upper limits for the time spent operating or at work. These rules are criticised as failing to neglect important causes of operator fatigue (CASA, 2014; Fourie, Holmes, Hildritch, Bourgeois-Bougrine, & Jackson, 2010; van Dongen & Mollicone, 2014). There have been moves to complement operating hours legislation with more comprehensive fatigue-risk management approaches, in which the causes and consequences of fatigue are monitored and mitigated within a supportive organisational system that can account for individual variations and the contexts of specific operations (Gander et al., 2011; Lerman et al., 2012). These so-called fatigue-risk management systems range from simple/informal approaches to more complex/formal approaches, but the core element is always the assessment and mitigation of fatigue risks.

Dawson and McCulloch (2005) describe how transport organisations should manage and mitigate risks along a whole chain of events that lead to fatigue accidents, from insufficient sleep opportunity afforded by work, insufficient sleep obtained by operators, fatigue-related symptoms at work, fatigue-related errors and fatigue incidents. They call this chain of risk events the fatigue-risk trajectory (FRT). The original FRT deals exclusively

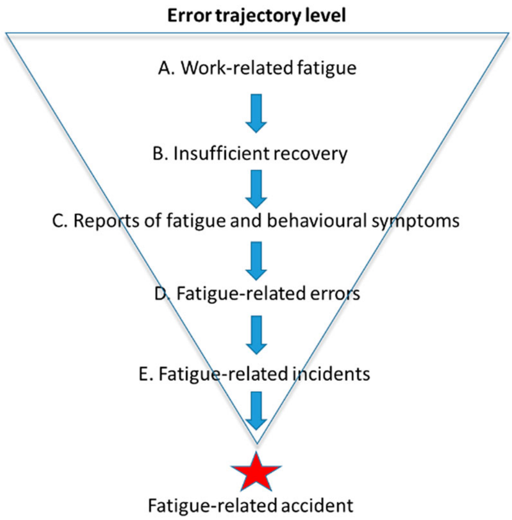

Figure 1. Dawson and McCulloch's (2005) fatigue-risk trajectory (FRT), in which several layers preceding a fatigue accident must be penetrated by active failures in the system. The first two levels have been modified to account for our broader conceptualisation of fatigue. Taken from Phillips (2016).

with sleep-related fatigue, but we can modify the first two levels to account for our broader operationalisation of fatigue, as shown in Figure 1.

How should managers control fatigue-related exposure and risks?

Effective fatigue-risk management will require that the risks are controlled at each of the five levels of the FRT, but at each level the transport risk manager will be faced by an array of potential monitoring and control measures. Several reviews are available to help them consider individual measures (Balkin, Horrey, Graeber, Czeisler, & Dinges, 2011; Belenky, Wu, & Jackson, 2011; Lerman et al., 2012; May & Baldwin, 2009; Rose & Giray, 2013). Perhaps most relevant are the reviews by Williamson and Friswell (2013a, 2013b), who present knowledge on measures for mitigating general work-related fatigue within an occupational health and safety framework, and Starren et al. (2008), who classify reactive and proactive fatigue measures specifically for the maritime sector. Anund et al. (2015) also discuss control measures in the context of a chain of decisions that need to be made to mitigate fatigue-related crash risks in different transport sectors. Despite the availability of such reviews, a gap is apparent, at least in some transport branches, between what is researched and how risk is managed (e.g. Phillips et al., 2015). While framework conditions are partly responsible for this, the situation could be improved if risks and measures were presented in ways that are consistent with risk management principles. These reviews would, therefore, be usefully supplemented by considering how monitoring and control measures can be selected for the mitigation of transport operator fatigue risks along the FRT.

The current paper structures measures per risk mitigated along the FRT, acting as a guide for fatigue-risk management as part of SMS. It is based on a review of measures for the mitigation of fatigue-related exposure and risk in operators of land- and sea-based transport forms (Phillips, 2016). As well as providing a more concise account, the current paper helps by disambiguating the concepts of fatigue-related exposure and risk factors, on the one side, and measures for monitoring and controlling them, on the other. The changes made in preparation of the current article have led to an altered grouping of checks and control measures for fatigue along the error trajectory, which we believe will be more coherent for those involved in risk management.

Method

The literature review is as described by Phillips (2016). In short, existing knowledge on fatigue measures available in the peer-reviewed scientific literature was retrieved by entering the terms "fatigue" +"countermeasure" + ["transport" or "driver" or "human operator" or "pilot" or "watchkeeper" or "bridge officer"] into the following search databases for the years from and including 1996 up to and including 2015:

- Science Direct
- TRID database combining posts from Transport Research Board's and OECD's international transport research documentation.

The article titles were reviewed, and articles discarded if they did not directly deal with measures to monitor or control fatigue-related exposure or risk factors. Knowledge of measures from the peer-reviewed literature was supplemented by content on other commercially available measures by performing a Google Scholar search using the words "fatigue countermeasures transport", in which case the first ten pages of "hits" were reviewed. Ninety-five key references were identified dealing with measures for fatigue in land- and sea-based transport (indicated with "*" in References).

For the current article, key references were supplemented with references giving background information available from the authors' existing databases. Monitoring and control measures identified from the studies were arranged into groups, by placing them with the corresponding fatigue-related exposure or risk factor addressed along the FRT. Notes were made on the application, pros/cons and effectiveness of each measure type, after reviewing the studies retrieved. The number of studies addressing each measure type was recorded. In many cases, a single study dealt with several types of measures. Study notes were used as the basis for summarising each measure type. In writing the summaries, we aimed to describe and outline the pros, cons and effectiveness of each measure type, rather than provide an exhaustive summary of each study.

Results

We identified 13 measures for the monitoring or control of fatigue-related exposure and risk factors from the literature. Table 1 arranges them along the FRT, per corresponding fatigue-related exposure or risk factor addressed. The review also identified two "systemic" measures (continuous learning and training/other), often cited in the literature as necessary for the integration of fatigue management into a coherent organisational risk management system. These are also indicated in Table 1.

Table 1. Fatigue-related exposure and risk factors in human transport operators and corresponding monitoring and control measures, structured using the FRT (cf. Fig. 1).

Error trajectory level	Exposure/risk factor	Monitoring	Control
A. Work	Sleep opportunity that work provides	Monitor planned/actual work hours (**4**)	Schedule design (**2**)
	Time of day/time-on-task	Monitor actual hours/ breaks (**4**)	Schedule design (**2**) Breaks and naps (**3**)
	Work content? Environment	–	Work content and environment design (**5**)
B. Recovery	Actual sleep obtained	Sleep monitoring (**6**)	Feedback on actual sleep time (**6**)
	Health status	Health screening (**7**)	Health treatment (**7**)
	Use of time outside of working hours	–	Promotion of sleep hygiene? operator recovery in free time (**8**)
C. Fatigue symptoms	Operator condition prior to work	Fitness-for-duty monitoring (**9**)	(Removal from operator duty)
	Operator condition while operating	Identification of fatigue symptoms while operating (**10**)	Containment of fatigue while operating (**11**)
D. Fatigue-related errors	Fatigue-related behaviour or performance error	Performance monitoring (**12**) Fatigue-proofing (**13**)	Performance assistance (**12**) Fatigue-proofing (**13**)
E. Fatigue-related incidents	Fatigue-related near-misses	(Reporting as part of continuous learning)	–

Staffing levels (**1**)

Continuous learning (**14**), Training, other systemic organisational measures (**15**)

Note: Numbers in bold indicate where each measure is presented in the main text following this table.

Below we describe each monitoring or control measure type, and the corresponding fatigue-related exposure/risk factor is addressed. The number of publications retrieved from our search addressing each measure type is given as an indication of weight of evidence for that measure.

A. Measures to monitor and control exposure to work-related fatigue

The timing of work influences both the levels of exertion and the opportunity for sleep and recovery from that exertion. The quality of work contributes to fatigue with respect to the type, number and intensity of tasks performed, as well as the resources available and the working environment.

1. Optimal staffing levels (5 publications). Staffing levels help determine how work is distributed among employees, and thus exposure to fatigue in terms of work hours and workload. As such, staffing has been considered the first level of defence in fatigue-risk management (Lerman et al., 2012; Moore-Ede, 2010). Understaffing will cause more problems during employee absences, more overtime and more last-minute schedule changes, leading to a larger discrepancy between planned and actual schedules worked. On the other hand, overstaffing may cause fatigue due to underload. Staffing levels have been linked directly to fatigue risks in the maritime sector, where increased automation exposes a minimal crew to fatigue during or after more intense operational phases such as port calls (Akhtar & Utne, 2015a, 2015b; Lützhöft, Grech, & Porathe, 2011). However, being able to staff sufficiently for varying demands associated with different operational phases is a challenge for many transport operations (Phillips et al., 2015).

Staffing levels are often kept at low to maximise productivity. Leaders will need to be convinced about the hidden health and safety costs of understaffing before staffing levels can be optimised (Lerman et al., 2012). Staffing can also be improved simply by planning better, for holidays, training or recruitment. Even the varying staffing demands of different operational phases can be planned for to some extent, both at sea and in road transport (e.g. extra staffing at depots to relieve the driver of loading tasks).

2. Schedule design (33 publications). Many operators work outside the hours of 07:00 and 18:00 h and in many cases work shifts or watches. Having to work at "unphysiological" times of the day (i.e. when one would otherwise be asleep) can cause acute fatigue not only due to circadian lows, but also because it is notoriously difficult to obtain sufficient sleep prior to such work. This is particularly true of night work and early starts, which have sustained effects on alertness (Åkerstedt & Landström, 1998; Phillips, 2014a; Roach, Sargent, Darwent, & Dawson, 2012). Work at unusual times also affects quality of life, and after many years of exposure, health and safety may be affected (Wright, Bogan, & Wyatt, 2013). Independently of the time of the day of work, fatigue can be caused if there has been a long time since the last sleep bout (sleep homeostasis), build-up of sleep debt due to recent work patterns or if the work or task has been conducted for several hours (Dorrian, Baulk, & Dawson, 2011). Naturalistic driving studies show exponential safety declines with time on shift, with roughly double the likelihood of accident or injury after 10 h relative to the first 8 h (Hanowski, Hickman, Fumero, Olson, & Dingus, 2007, 2009).

Scheduling work to account for fatigue mitigates three important fatigue risks: insufficient sleep opportunity, work at "unphysiological" time of day and too long time-on-task. The importance of scheduling in limiting exposure to fatigue is reflected by regulations that detail the need for scheduling to account for fatigue in addition to operating efficiencies (Houtman et al., 2005). Several tools are available based on biomathematical models, allowing schedulers to make evidence-based predictions about the fatigue-risk levels or performance/safety levels that their schedules will induce (CASA, 2010). These vary in complexity from Åkerstedt's (2010) tool based on a simple formula, through to web-based crew systems linked to scheduling software (Gunther, 2008). CASA (2014) reviewed seven biomathematical models with several applications in fatigue-risk management:

- optimisation of schedules for fatigue mitigation;
- planning for irregular operations;
- analysing fatigue as a contributor to accidents and
- as the basis of software or smartphone apps for individual fatigue prediction.

Managers should consider that the models have limitations. Some are based on work–rest data rather than actual sleep–wake times, and some do not account for task performance in addition to sleep drives (Folkard, Robertson, & Spencer, 2007). Group-level data are often input, and group-level predictions made, but managers should remember there is large variability in the sleep obtained by individual operators (Darwent, Dawson, Paterson, Roach, & Ferguson, 2015). Finally, there are challenges in setting acceptable limits for fatigue (Dawson, Ian Noy, Härmä, Åkerstedt, & Belenky, 2011). Given such limitations, the tools should never be used as the sole means of designing or justifying schedules.

There is evidence that interventions to adjust schedules to account for fatigue result in increased sleep opportunities (Dawson et al., 2011), benefit worker health (Neil-Sztramko, Pahwa, Demers, & Gotay, 2004) and reduce transport accidents (Gertler, Popkin, Nelson, & O'Neil, 2002; McCallum, Sanquist, Mitler, & Krueger, 2003; Moore-Ede et al., 2004). There are also claims that the functionality of model-based schedule redesign has been demonstrated, but some authors call for further evidence that fatigue reductions can be obtained (Williamson & Friswell, 2013a,2013b). Finally, scheduling recommendations must also consider the operational constraints of each transport mode.

3. Sufficient frequency and duration of breaks (16 publications). The frequency and duration of breaks are important for limiting exposure to time-on-task fatigue (Belenky & Åkerstedt, 2011; Caldwell, 2001; Jay, Aisbett, Sprajcer, & Ferguson, 2015; Reyner, Flately, & Brown, 2006). There is evidence that regular breaks may ultimately reduce crash risk for truck drivers (Stevenson et al., 2014). Break timings are often determined by legislation stipulating minimum break duration and frequencies, but biomathematical tools can help optimise them. The challenge for some managers will be in providing sufficient flexibility for optimal breaks in the face of delays or other varying operational pressures. Professional drivers cannot always predict when and where they will be able to take a break, but planning (e.g. checking location of desirable rest stops) has been found to be an important tactic to counteract fatigue (Gershon, Shinar, Oron-Gilad, Parmet, & Ronen, 2011). Overall, it seems more should be done to make explicit the differences between operators and managers in terms of desired break timing, discrepancies between planned and actual break times, and compatibility with regulations. Managers should also consider the extent to which breaks promote recovery. On ships, for example, operators are often exposed to vibration, noise, motion and interruptions during rest periods (Calhoun & Lamb, 1999).

4. Addressing discrepancies between planned and actual hours worked (13 publications). Regardless of attempts to limit fatigue by optimising schedules, the schedules ultimately worked by operators can deviate from those planned. There can be last-minute changes due to insufficient staffing or operational pressures, or employees themselves may wish to swap schedules or work overtime (Phillips et al., 2015). In addition to recording actual working patterns, employers should therefore assess the effects of deviations on fatigue risks, to estimate whether the discrepancy needs to be addressed in cooperation with employees (Office of Rail Regulation, 2012).

5. Design of work content and work environment (10 publications). There is considerable variation in the primary and secondary tasks that different transport operators perform (Phillips, 2014a). Work content and environment analyses can form the basis of mitigating actions to minimise the extent to which (i) the main operating task is fatiguing (Hancock et al., 2012), and (ii) secondary tasks increase the chance of fatigue (overload) occurring during the main operating task (Soccolich et al., 2013; Tzamalouka, Papadakaki, & Chliaoutakis, 2005).

Regarding (i), it will be important to assess the extent to which there is underload or overload (May & Baldwin, 2009). While automation is a potential source of increasing fatigue for operators who are passive observers of the system (increasing automation of bridge at sea and of the train/truck driver task), those required to multitask in busy station, urban or port environments may be subject to overload (Phillips et al., 2015). Adaptive automation solutions aim to reduce active task fatigue at times when operator performance is most susceptible to fatigue risks, for example by giving audible instead of visual messages if the driver is visually overloaded. If underload is the problem, the driver may be given secondary tasks to perform, for example, cancelling of an auditory alarm (Oran-Gilad, Ronen, & Shinar, 2008).

Regarding (ii), managers can plot different tasks performed over time to reveal periods in which the operator will be particularly susceptible to fatigue risks, so that mitigating actions can be applied to risky periods (Friswell & Williamson, 2005). For example there may be a need for extra vigilance for those working the first bridge watch immediately following a busy port call, who have not yet had a chance to recuperate.

Which measures are employed will depend on the characteristics of the transport operation, but job redesign is important to consider, including, for example, reassignment of secondary tasks to or away from the operator, or measures to disrupt spells of monotony (Houtman et al., 2005).

B. Measures to monitor and control insufficient recovery from work fatigue

In addition to insufficient opportunity for recovery, operators may be in life situations that are not conducive to recovery from previous work (Phillips, 2014a). In some cases, training may be needed to educate operators about how to recover sufficiently from work (see measure 15), and should supplement the following monitoring and control measures.

6. Sleep monitoring and feedback (23 publications). No measure to control fatigue while operating is as effective as sufficient prior sleep aligned with circadian rhythms (MacLean, Davies, & Thiele, 2003). Assuming work affords appropriate sleep opportunity, individual operators are best placed to manage their own sleep, and can be assisted by tailored feedback on how to improve sleep hygiene. The most practical way to measure individual sleep is using a wrist-worn actigraph, which registers movement data using an accelerometer (Belenky et al., 2011; IATA/ICAO/IFALPA, 2015). Recent years have witnessed the rapid emergence of similar technology incorporated into wearables and mobile apps, which also give feedback and tips about how to improve sleep hygiene (CASA, 2014; Hao, Xing, & Zhou, 2013). Some specialists provide tailor-made solutions for transport operators (e.g. Fatigue Science).

Actigraphs can also be used to help evaluate company interventions aiming to improve driver sleep. Sleep data can also be input into schedule analysis software to help predict group-level fatigue risks and alter schedules accordingly. Such data can also be provided by paper-, mobile- or tablet-based sleep logs filled out by the operators themselves (IATA/ICAO/IFALPA, 2015). Managers should note, however, that it is not the logging itself that is helpful, rather what is done with the information.

7. Health screening and treatment (29 publications). Sleep disorders or health conditions influence how long and well the employee sleeps, and therefore recovery from work fatigue (Smolensky, Di Milia, Ohayon, & Philip, 2011). In terms of professional operator prevalence, sleep apnoea is a problem, and has been linked to excessive daytime sleepiness and increased risk of car crashes (Belenky & Åkerstedt, 2011). Work itself may be the cause of some disorders (e.g. insufficient sleep syndrome and shift work disorder) (Lerman et al., 2012).

Managers should screen and treat both existing and potential employees for health problems affecting sleep (Hakkanen & Summala, 2000), and treat and evaluate treatment outcomes, which in the case of apnoea are often positive given adherence to the treatment regime (Belenky et al., 2011; Wright et al., 2013). Medical screening can be part of a company check-up, or occur as a follow-up to a one-off site visit or survey following training session about sleep disorders (Howard, Wilson, Hare, Swann, & Pierce, 2009; Lockley, O'Brien, & Patton, 2009; Smiley et al., 2009). Managers can also introduce effective control measures including cessation of shift work, or naps and stimulants before shift (Wright et al., 2013).

Phillips and Sagberg (2010) conclude that 41% of attempts at fatigue management include screening and treating for sleep disorders, and positive effects are being increasingly documented.

8. Promotion of operator recovery during non-work time (13 publications). Rest facilities at stations, termini or hotel rooms are recommended by Office of Rail Regulation (2012) for those with short free periods (less than 14 h) between shifts and/or long commutes home. Larger organisations should consider habitability studies at sleeping facilities to optimise rest (McCallum et al., 2003; Poore & Hartley, 1998). On ships, the off-watch physical and psychosocial environments will need to be considered as important influences on fatigue (Sonnentag & Fritz, 2007). While managers may hesitate to engage operators in a dialogue about their free time, research on well-being provides legitimate ways in which they can approach the influence of non-work time on fatigue at work (Daniel & Sonnentag, 2014; Fritz, Sonnentag, Spector, & McInroe, 2010; Oerlemans, Bakker, & Demerouti, 2014). Participative schedule redesign may help increase awareness about the importance of free-time activity on fatigue at work (Nielsen, Nielsen, Munk-Madsen, & Hartmann-Petersen, 2010). Coaching and empowerment of operators to adjust own rest hours, together with feedback on sleep habits, appear to be an effective approach (Moore-Ede, Heitmann, Dawson, & Guttkuhn, 2005). "Sleep contracts", which include standards on sleep and a framework for reacting to fatigue, are not widely used, but can promote employee recovery during free time (Gall, 2006; Holmes, Baker, & Jackson, 2006). Finally, we should note that there will always be days when it is not possible for the operator to get enough sleep. Strategies should be identified and communicated to operators so that they know what to do in such cases.

C. Measures to detect and control fatigue symptoms before and during operation.

9. Fitness-for-duty monitoring (19 publications). Used just before an operating period, fitness-for-duty tests assess the degree to which operators have recovered from previous work in their free time, such that severe fatigue does not develop in operators who are insufficiently recovered. Several portable computer-based tests or mobile apps are now available, generating performance-based indicators of fitness for duty. Psychomotor vigilance tests (PVTs) are palmtop tests that can be carried out in 10 minutes by the operator, either before starting duty or during breaks. Some authors claim PVTs are valid as tests of sleep-related performance deficits (Jay, Dawson, & Lamond, 2005; van Dongen & Mollicone, 2014), and are often rated highly relative to other fitness-for-duty tests (Dawson, Searle, & Paterson, 2014). However, there are still challenges such as age-dependent variations in response times. Other fitness-for-duty tests include bench-top or portable devices that monitor eye/pupil movements (e.g. Ahlstrom et al., 2013; Shahidi, Southward, & Ahmadian, 2009). Fitness-for-duty devices can also be used to calibrate biomathematical software to improve prediction of fatigue levels for the individual driver (Balkin et al., 2011). Tests on higher mental abilities (working memory and decision-making) may also be useful for operators (Tyagi, Shen, Shao, & Li, 2009).

Despite advances in technology, managers should not overlook simple, quicker subjective ratings based on valid and reliable survey items assessing sleepiness or need for recovery (Åkerstedt, Anund, Axelsson, & Kecklund, 2014, van Veldhoven & Broersen, 2003). These tests can also be performed using a portable tablet or phone, to help generate organisational data.

Ideally, both objective and subjective tests would be used to inform managers and drivers about whether it is safe for the driver to embark on the trip (Wilschut, Caljouw, & Valk, 2009). More field studies are needed for the different fitness-for-duty indicators, as well as guidelines on establishing "fail levels", on operator acceptance and on what course of action an "unfit" result should trigger.

10. Identify fatigue symptoms while operating (32 publications). Fatigue symptoms can be identified by encouraging or prompting standardised self-assessments by operators, or by objective measurements of developing symptoms.

Subjective identification of symptoms. Most operators know when they are sleepy, and the subjective rating of sleepiness has been shown to be just as valid as objective measures as a sensitive and valid an indicator of sleepiness (Åkerstedt et al., 2014). Operators of all transport modes should have knowledge of their own developing fatigue level – awareness of being fatigued is a key factor for the decision of whether to use countermeasures, stop working, or report being unfit to work. Self-awareness can be optimised by training operators to recognise specific physical, mental and emotional signs of fatigue in themselves and others (Lerman et al., 2012).

Objective identification of symptoms. Objective measurement of fatigue symptoms using technology addresses concerns that self-assessments can be context-dependent. For lone operators, without peer observations, these technologies are even more important. Valid technologies for measuring indicators of fatigue measure either physiological indicators (eye, facial or head characteristics or brain-wave activity) or performance indicators (addressed below) (Craig, Tran, & Wijesuriya, 2011; Dinges, Maislin, Brewster, Krueger, & Carroll, 2005; Hanowski, Hickman, Blanco, & Fitch, 2011; Lal & Craig, 2001; Sigari, Pourshahabi, Soryani, & Fathy, 2014). Several systems are commercially available, such as the PERCLOS/CoPilot-type systems that monitor eyes by video and calculates the percentage of time per minute that they eyelid covers 80% of the pupil. The Optalert system has been shown to lead to small reductions in sleepiness in operators (Aidman, Chadunow, Johnson, & Reece, 2015). Most sytems use algorithms to track alertness decreases, and may trigger information/feedback to the driver (e.g. time spent with eyes closed) or, where systems are centralised, to a control centre. It is also becoming increasingly viable to monitor brain waves as indicators of fatigue using polysomnography with technologies such as SmartCap or B-Alert (Dawson et al., 2014). Despite such developments, recent reviews still highlight need to establish performance validity in the field of any technology for the objective measurement of fatigue symptoms (Dawson et al., 2014; Lerman et al., 2012). Whatever technology is implemented to measure fatigue objectively, Lerman et al. (2012) raises important questions that transport risk managers need to consider, e.g. When will the test be administered? Will operator participation be mandatory? Who will obtain the results and what actions will be taken based on the results?

11. Measures to contain fatigue while operating (21 publications). Task-related fatigue can be relieved by technologies varying work demand levels, tasks or regular operating breaks, but sleep-related fatigue is resistant to such strategies (May & Baldwin, 2009; Hartley et al., 2013). Instead, the operator either needs to stop and sleep/nap, or use energy or caffeine drinks (Åkerstedt & Landström, 1998; Snel & Lorist, 2011). The latter measures are important in the rail and especially the road sector, where lone operators must act to mitigate fatigue symptoms that develop while operating. At sea and in some land-based branches, there may also be opportunities for rest from being relieved from duties by colleagues.

Concerning effects, most research has focused on those against sleep-related fatigue. Napping and caffeine and energy drinks in addition to regular stops have been shown be effective temporary countermeasures to sleep-related fatigue occurring while operating (Anund et al., 2015; Gershon, Shinar, & Ronen, 2009; IATA/ICAO/IFALPA, 2015; Reyner & Horne, 2002; Ronen, Oron-Gilad, & Gershon, 2014; Rose & Giray, 2013). However, there will be variation in the extent to which individuals respond to these measures and there may be negative effects on fatigue in the longer term if they are used frequently.

Even though operators recognise the effectiveness of stopping and sleeping and caffeine intake, they tend to rely on less effective methods such as winding the window down or eating (Nordbakke, 2004; Nordbakke & Sagberg, 2007). Measures aimed at motivating drivers to select the correct fatigue countermeasure are, therefore, more important than education about the most effective countermeasures (Armstrong, Obst, Banks, & Smith, 2010; Watling, Armstrong, Obst, & Smith, 2014; Watling, 2014). Drivers must perceive that they can employ effective measures despite operational constraints (Pylkkönen, Sihvola, Hyvärinen, Puttonen, & Hublin, 2015).

D. Measures to detect and contain fatigue-related operating errors

Here the concern is what can be done to reduce the chance that fatigue-related errors lead to incidents and accidents.

12. Performance assistance (12 publications). In the road sector, fatigue-related errors will normally begin to manifest themselves as small decrements in driving performance. Systems monitoring embedded performance measures are available to track the operating task in terms of lane position, speed, braking, distance to vehicle in front, acceleration or fuel economy (e.g. C2-170, SafeTrack, MobilEye, AutoVue, Delphi, Roadguard and ASTiD). Embedded performance measures can also be used trigger other systems giving automated driver assistance (Dorrian, Roach, Fletcher, & Dawson, 2006; Liu, Hosking, & Lenné, 2009). Simply providing drivers feedback on, for example, vehicle positioning has been found to reduce lane tracking variability significantly, although the effect will only be temporary and there will be extra cost to the driver (Dinges et al., 2005).

Embedded performance systems offer advantages over physiological measurement of fatigue, in that they are non-intrusive and provide a direct measure of safety performance, the ultimate concern (Dawson et al., 2014). There are concerns, however, about the number of false alarms generated and whether the drivers begin to rely on these systems as safety nets, making it possible for them to drive further while fatigued.

In the rail sector, there are already systems in place that assist performance to a large extent (ATC and ETMS), and the challenge from fatigue-related errors may be more linked to higher level cognitive processes such as decision-making (Phillips & Sagberg, 2010). In the maritime sector, the navigation process is highly automated, but fatigue-related performance decrements may only manifest themselves in situations in which officers need to intervene. Dead-man's switch systems in rail and Bridge Navigational Watch System and associated alarms at sea are reviewed by Anund et al. (2015). Both attempt to mitigate the effects of a sleeping operator – which we consider here to be a fatigue-related error – by alerting others who may be able to help before an accident occurs.

13. Fatigue-proofing (3 publications). Dawson, Chapman, and Thomas (2012) promote the idea of "fatigue-proofing" strategies, involving pre-signalling of elevated risk and increased scrutiny of potential error, to make transport operations more resilient to the effects of operator fatigue in situations where it cannot be avoided. The authors give examples of pilots at sea asking helmsmen to call back commands to ensure what was said was correct, received and actioned; and of air pilots who openly identify themselves as fatigued to co-pilots when not adequately rested. Since many such strategies have evolved naturally in the field, they already account for cultural contexts and are accepted by workers. Standardisation of fatigue-proofing will require research into consistency of strategies in use, their effectiveness in terms of fatigue control and development of standard criteria for practice.

Though not covered by Dawson et al. (2012), formal "fatigue-proofing" strategies can also be identified. Most technological safeguards ensuring human errors do not lead to incidents or accidents are relevant here. For example, in bus transport, start inhibition, where buses will not leave a bus stop until the doors are closed, might help prevent fatigue-related accidents (Cafiso, Di Graziano, & Pappalardo, 2013). There may be greater potential for systems which ensure that operators must react to confirm they have perceived key safety-relevant signals, such as in rail or at sea, such that fatigue-related errors can be detected and managed as they happen (Wilde & Stinson, 1983).

Systemic measures to support risk mitigation at all FRT levels

In line with SMS thinking, the organisation will need to put in place generic measures to support the implementation of measures to monitor and control fatigue-related exposure and risk factors at each of the five levels of the FRT. These are dealt with briefly here.

14. Organisational learning (21 publications). The organisation should monitor and learn from barrier failures at each level of the FRT, to improve those measures mitigating errors earlier on in the trajectory. It should establish systematic data collection procedures for gathering information about the role of fatigue in incidents and accidents (e.g. Gander, Marshall, Bolger, & Girling, 2005; IATA/ICAO/IFALPA, 2015). Analysis of fatigue-related safety critical events from naturalistic driving studies may be part of the fleet management system in larger fleets, and in smaller fleets, dashboard-mounted cameras may help with incident analyses (Dozza & Gonzalez, 2012).

15. Training/other systemic organisational measures (28 publications).

> *Training and education.* As well as inform operators and risk managers about the containment of fatigue and importance of scheduling and optimal recovery methods, organisations should educate managers, schedulers, employees, employee representatives and unions, and transport chain stakeholders of the need for and nature of the company-specific fatigue risk management. Phillips and Sagberg (2010) describe some standard training modules. Training is relatively inexpensive, but often places the onus on individual operators. The effects on

actual performance are uncertain and group discussions may be just as effective (Williamson & Friswell, 2013a, 2013b).

Management commitment. There are now many studies indicating that management commitment is the cornerstone of effective organisational safety management (Nævestad, 2016). Research demonstrating definite benefits for the business intending to implement fatigue risk management is therefore needed to stimulate management commitment (Akhtar & Utne, 2013; Murray, White, & Ison, 2012).

Recruitment and selection. Psychometric tests and behaviourally-anchored competency interviews can be used to select those operators more suited to shiftwork, or medical screens can ensure operators are free from sleep-related disorders (Trutschel et al., 2009).

Safety climate and culture. The importance of culture in effective fatigue management is evidenced not least by persistent underreporting of fatigue in the maritime sector (Smith, 2006). Just culture is important also for open reporting of fatigue symptoms and continuous learning in land-based operators (Lee, Huang, Murphy, Robertson, & Garabet, 2016).

Summary and discussion

We have identified from the literature 13 types of fatigue monitoring and control measures, and two systemic measures, to address fatigue-related risks in the context of SMS. We have arranged these measures along the FRT to assist those who manage risks faced by land- and sea-based transport operators (Table 1).

After initial risk analysis, the need for barriers at each level of the error trajectory should be considered to minimise the chance that work causes fatigue-related accidents. Risk managers should consider the manifestation of fatigue along the whole trajectory, and monitor fatigue risks accordingly, using the results to evaluate and evolve the barriers preceding that step. The extent of safety barriers required and the comprehensiveness of the measures they comprise will depend on the likelihood of a fatigue-related incident and the seriousness of its consequences. The precise choice of measures comprising each barrier will depend on the company's existing resources, competence, technology, infrastructure and culture, the nature of its work or business (e.g. type of goods transported, short or long haul), the framework conditions and its regulatory context. Finally, risk management should be integrated into an organisational system that is coherent (policies, procedures, data systems, etc.) and supportive (leadership commitment, just culture, etc.) in line with the principles of Fatigue Risk Management Systems (Gander et al., 2011; Lerman et al., 2012).

Some of the measures described in Table 1 can be implemented at more than one FRT level. For instance, breaks and naps can be designed not only to give a prophylactic effect, but also in response to developing fatigue symptoms (as part of fatigue containment while operating). Some measures will help to control both acute task- or sleep-related fatigue, and chronic fatigue. Task-related fatigue that is not mitigated by breaks and naps will lead directly to fatigue symptoms within a single operating bout, and the model indicates that measures should be implemented to detect and identify these symptoms such that task-related fatigue can be contained and fatigue-related errors avoided.

Specific examples of each measure type are listed in Table 2, which also gives an idea of different approaches that might be taken by organisations of different sizes with different resources. The table illustrates that fatigue-risk management need not be complicated, and

Table 2. Specific and comprehensive examples and pros and cons for each measure type.

Measure type		Two examples Simple, for example, small truck company (1) Comprehensive, for example, large shipping fleet (2)	Pros	Cons
1	Optimal staffing	Increase (/decrease) number of operators (1 and 2)	Understaffing a main determinant of fatigue exposure	Expensive
2	Schedule design	Use of Åkerstedt's (2010) formula or simple guidelines (e.g. Boivin, 2000) (1). Schedule optimisation based on biomathematical modelling software with input data on actual sleep times (2)	Tackles problem of insufficient sleep, a main cause of transport operator fatigue	Optimal design constrained by need for operational efficiencies. Software only as good as models and data input. Staff may not wish to work optimal schedules
3	Breaks and naps	Plan rest stops in advance (1). Evaluation of strategic napping intervention (2)	Temporary alleviation of time-on-task fatigue, acute sleepiness	May be operational constraints, napping may not always be possible or desirable (sleep inertia)
4	Actual hours worked	Compare self-reports/logs of actual working hours with planned schedules (1). Analyse change in fatigue-risk index for actual schedules worked versus those planned (2)	Can be large deviations between planned + actual hours worked.	Staff? Managers like flexible schedules, staff may like working overtime
5	Optimise work content	Survey to identify and reduce secondary tasks causing fatigue (1). Human factors? Task analysis and optimisation by independent consultant (2)	Varied work content may increase well-being	Often not possible to change work content in transport operations
6	Monitor actual sleep	Wearables giving feedback and tips on sleep improvement via mobile app (1). Centralised collection of actigraph data to feed into schedule design (2)	Addresses head-on extent to which operators recover from previous work. In line with the principle of "control at source"	Personal privacy issues
7	Health screening and treatment	Develop fatigue checklist in collaboration with doctor to be used at annual check-up (1). Monthly screening by occupational health service with follow up of disorders influencing fatigue (2)	Can be integrated with existing organisational health measures	Ethical issues, for example, should managers know about operators with disorders?
8	Promote operator recovery	Provide taxi to/from ship/depots after long operating periods (1). Sleeping facilities at depots, sleep contracts, family training (2)	Improves safety for other road users	Expensive
9	Monitor fitness-for-duty	Mobile app – PVT (1). PVT results fed into FRMS (2)	More reliable tests are time-consuming	Predictive validity
10	Monitor fatigue symptoms while operating	Self-assessment with Tiredness Symptoms Scale (1). Embedded performance monitoring, facial/eye technology (2)	Subjective assessment can be valid and reliable	Operators know when they are tired but operational constraints prevent action

(*Continued*)

Table 2. Continued.

Measure type		Two examples Simple, for example, small truck company (1) Comprehensive, for example, large shipping fleet (2)	Pros	Cons
11	Contain fatigue while operating	Promote stopping and sleeping (1). Develop guidelines of when to stop and sleep (2)	Only way to prevent sleepiness is sleep	Need to address logistical? Operational constraints
12	Performance assistance technology	Use evidence-based technologies that reduce fatigue (2)	Technologies increasingly available	Does not tackle sleep-related fatigue
13	Fatigue-proofing	Increase customer awareness and involvement (1). Technological safeguards (2)	Addresses effects of fatigue on performance	Can be expensive. Generally little known about reliability.
14	Continuous learning	Regular review and optimisation of measures (1). Safety assurance, data-driven evaluation of each risk level at regular meetings (2)	–	–
15	Training? Other systemic	Driver training (1). Training all staff in FRMS (2)	–	–

only some of the measures may prove necessary. Using this approach, fatigue-risk management should be possible even for small transport companies with only a handful of operators, even though this may not be part of formal fatigue-risk management.

Managers will want to implement measures known to be effective. For certain measures, there is good evidence that they lead to reductions in fatigue and improvements in safety, for example, schedule design interventions, job design interventions, health management and stopping to contain fatigue while operating. Despite scientific support that they would reduce fatigue, field research is needed to evaluate the effects of interventions based on staffing-level optimisation, actual/scheduled hours analyses, recovery promotion, fitness-for-duty monitoring, performance assistance and formalised fatigue-proofing strategies. The number of publications retrieved for each measure type shows that there is a lack of research into staffing levels, accounting for actual hours worked, field-based interventions of performance assistance technology and fatigue-proofing. Moreover, there is a need to evaluate the implementation of whole systems for fatigue-risk management to establish a business case for managing fatigue and stimulate management engagement.

The lack of robust field evaluations prevents the ranking of measures in order of effectiveness. It is also difficult to identify effect measures that are used consistently enough as to provide a basis for comparison of different control measures for fatigue. However, several authors point to evidence that the control of sleep-related fatigue should be prioritised if transport operator fatigue is to be tackled effectively. This implies control using schedule design, analysis of actual hours worked, sleep monitoring, health screening, and monitoring and control of sleepiness before and during operation should be prioritised. The best available evidence appears to be for schedule design and health screening, and these measures are among the most popular used in fatigue-risk management programmes (Phillips & Sagberg, 2010).

Independent of type and size, all companies must be convinced that accounting for fatigue does not place it at a competitive disadvantage. A first step in this process would be to develop a standard tool for the systematic measurement of a fatigue-risk management system, for example, number of critical elements in place, and fatigue-risk culture.

Smart cards that record start/end times in relation to planned schedules, ensure that fatigue training or health check-ups are up to date and include other data to monitor the effectiveness of FRT measures are exciting developments. Such technology could also be used to monitor trends in shift swapping and overtime and sickness absence for any warning signs that the workforce or individuals are being subjected to increasing fatigue. Innovative research is needed in this area to demonstrate the possibilities to transport risk managers.

This paper focuses on the role of occupational risk managers in organisations employing land- and sea-based operators. This should not detract from the need to involve other transport chain actors in fatigue management. Shipping agents, customers, etc., could help with the approach to fatigue-risk management described here, by taking increased responsibility for their own influence on operator fatigue (e.g. setting delivery times), and by setting demands on transport company to demonstrate certification in fatigue-risk management. If sufficient trust could be established between buyers, drivers and their employers, customers/depot managers might also check for fatigue risks during operations. Regulatory authorities also play an important role in conducting information campaigns and fatigue-audits, stimulating the development of fatigue-risk management and evaluating the effectiveness of hours of service regulation.

Study limitations and future research

While an attempt was made to carry out our review systematically, we found it necessary to include reports that we knew of that did not come up in the literature review. Indeed, there is a large amount of "grey literature" in this area that does not show up in literature searches. Practitioners in this area also have valuable knowledge of this literature as well as hands-on experience, and we have not attempted to gather and summarise their knowledge. However, we assume that the most important risk factors and control measures will have made their way into the robust peer-review literature, where the results of evaluations would also tend to be more reliable.

Rapid developments in technology expand the possibilities for fatigue mitigation at a rapid rate, and some measures we describe may already be out of date by the time this article is published. This should not detract from the main aim of this article, which is to describe how risk managers should approach the selection of measures and to summarise the main measure types that can be selected.

Earlier on in this article we refer to a gap between available research on fatigue and what is done to manage the risks in practice, and this may help explain why fatigue continues to cause problems in transport. Further research is required to explain this translational gap, to investigate both *why* measures are not implemented, and, if they are implemented, whether implementation is optimal. The latter is an important aspect of risk management that the research literature overlooks. In our experience, practitioners consider implementation to be the most critical element in fatigue-risk management, and a participative approach involving collaboration between researchers, consultants, employers and employees is often most fruitful.

Conclusion

Fifteen types of measure have been identified and arranged along a risk trajectory, to assist organisations in the mitigation of fatigue in employee operators of land- and sea-based transport forms. The resulting framework can be used as the basis of comprehensive fatigue-risk management approaches in small or large organisations. To inform transport risk managers further, field research is needed evaluating the effectiveness of individual measures and whole fatigue-risk management interventions.

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