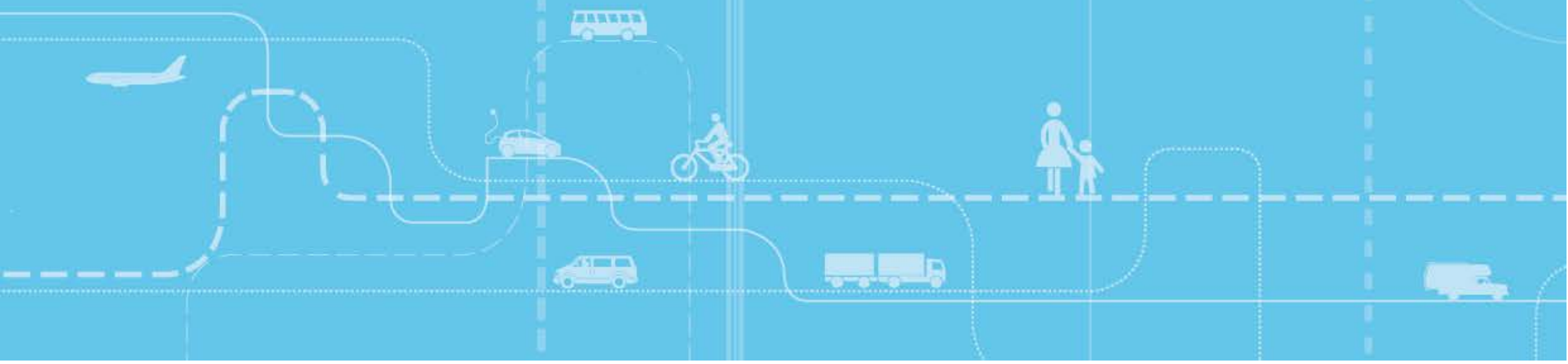
TØI report 1351/2014

Ross Owen Phillips

Institute of Transport Economics
Norwegian Centre for Transport Research

What is fatigue and how does it affect the safety performance of human transport operators?

Fatigue in Transport Report I



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Summary:

The ability to manage human fatigue in transport operations would be improved by a shared understanding of what fatigue is, how it should be measured, and how it affects safety performance. This may be achieved by a broader operationalization of fatigue, which would allow commonly studied aspects of fatigue to be considered alongside each other, and make explicit those aspects of fatigue that individual studies do and do not account for. According to such an operationalization, fatigue should be measured in terms of experience, physiological state and performance. In studying the effects of fatigue on operators, there would be a need to for greater consideration of its longer-term effects, and its motivational aspects. To understand its performance effects would require that we attend to the systematic interaction of sleep history, time of day, time at work, and time on task, in the context of factors describing various aspects of work and non-work life.

Sammendrag:

Prioriteringen av trøtthet som en risikofaktor i transport er avhengig av en delt forståelse om trøtthet, om hvordan det bør måles, og om hvordan det påvirker sikkerhet. En felles forståelse kunne oppnås ved å anerkjenne trøtthet som et bredt begrep med ulike dimensjoner som bør måles, og som sammen beskriver erfaringsmessige aspekter, fysiologiske aspekter, og prestasjon. En slik tilnærming ville klargjøre aspekter av trøtthet som ulike studier ikke tar hensyn til. Det er også behov for økt overveielse av trøtthets langsiktige effekter hos menneskelige operatører. For å forstå hvordan trøtthet påvirker prestasjon, må vi ta hensyn til interaksjonene mellom søvn, døgnrytme, «time-on-task» i sammenheng med faktorer som beskriver ulike aspekter av livet, både innenfor og utenfor arbeid.

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Institute of Transport Economics
Gaustadalleen 21, 0349 Oslo, Norway
Telefon 22 57 38 00 - www.toi.no

Transportøkonomisk Institutt
Gaustadalleen 21, 0349 Oslo
Telefon 22 57 38 00 - www.toi.no

Preface

This report is part of the project «Fatigue in Transport» (FiT), which has been carried out within the TRANSIKK programme («Transport sikkerhet») of the Research Council of Norway. The main objective of the project was to increase what we know about fatigue in human transport operators in the road, maritime and rail sectors in Norway. In an early phase of the project, it became clear that we needed to operationalise fatigue explicitly, not least in order to be able to compare findings from Norway with those from other countries. On investigation, however, we found few accounts of how fatigue should be operationalised for the study of human transport operators. This report attempts to fill this gap by explaining how we defined and thought about fatigue in relation to human operator safety. It also explains how we surveyed and assessed operationalised measures of fatigue for the purposes of assessing its health and safety implications. We hope that this report may be of use to those embarking on studies of fatigue in the future, who may also face the daunting task of reviewing the considerable literature on fatigue in order to decide how to measure and think about it.

The project manager and report author, Ross Owen Phillips, wishes to thank Torkel Bjørnskau, Fridulv Sagberg, and Tor-Olav Nævestad for comments and discussions in the development of the report. Sagberg also translated the summary into Norwegian. Torkel Bjørnskau has also quality assured the report. Trude Rømming has been involved in editing the report and preparing it for publication.

Oslo, November 2014
Institute of Transport Economics (TØI)

Gunnar Lindberg
Managing Director

Torkel Bjørnskau
Chief Research Political Scientist

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There is a long-standing lack of consensus about what fatigue is or how it should be measured. The literature is peppered with divergent attempts to operationalize the term, and unless the reader understands precisely how fatigue has been operationalized by the different studies, a comparison of prevalence rates is almost meaningless. Convergence on the operationalization of fatigue is required for improved consistency of measurement, to allow comparisons across findings and increase the priority of fatigue as a transport safety risk in relation to those that are more easily measured. Convergence would also help managers understand the effects of fatigue as more demands are placed on workers in a 24-hour society increasing in complexity and efficiency. This report seeks to evolve the literature towards convergence on operationalizing fatigue for study in human transport operators. This is achieved in two main ways. Firstly, a consensus definition is generated for the study of the effect of fatigue on safety-related functions of human transport operators through reviewing existing attempts at definition. Secondly, explicit links are drawn between the effects of fatigue and the safety functions of human transport operators.

What is fatigue?

An important issue to address when operationalizing fatigue, is whether or not the concept should be treated as synonymous with sleepiness. Sleepiness is a clear and serious threat to transport safety. We understand sleepiness a lot more than we understand other components of fatigue, at operational, theoretical and physiological levels. Based on homeostatic and circadian influences, we can make reasonably successful predictions of average sleepiness for a groups of operators at varying times of the day, after they have followed a given work schedule, or have been given a certain series of sleep opportunities. An obvious question then is why not focus on sleepiness as a safety risk for human transport operators, and ignore the confusing concept of fatigue altogether? There are several answers. Firstly, we wish to understand the effects of sustained work and working while tired on performance, and sleepiness models say little about this. Secondly, even though they may not be sleepy, human operators may still be fatigued such that performance or latent performance is affected. Thirdly, vigilance is a central task for all transport operators, and task-related fatigue can have strong effects on vigilance. And fourthly, we are interested in accounting for how cumulative fatigue related to stress and other energetic constructs may lead to performance reductions. We therefore wish to operationalise fatigue as a broad concept that can capture not only the effects of sleepiness on safety in human transport operators, but those of task- and job-related effects, in addition to the longer term interactive effects of health and safety.

A review of existing attempts at definition finds that the broader concept of fatigue cannot be distilled to a single dimension, but has multidimensional aspects, which are dynamically interdependent and do not fully correlate. These aspects describe how fatigue manifests itself in subjective experience, physiology and performance. The impact of these multiple components of fatigue on the operator must be considered together within a systems perspective. From our review we have evolved a broad multidimensional definition of fatigue that is useful for the study of fatigue in human transport operators, and other researchers may wish to converge on this. It is meant as a contextual definition that can be used as the basis for narrower operational definitions to be used for specific studies of aspects of fatigue. The definition is as follows.

Fatigue is a suboptimal psychophysiological condition caused by exertion. The degree and dimensional character of the condition depends on the form, dynamics and context of exertion. The context of exertion is described by the value and meaning of performance to the individual; rest and sleep history; circadian effects; psychosocial factors spanning work and home life; individual traits; diet; health, fitness and other individual states; and environmental conditions. The fatigue condition results in changes in strategies or resource use such that original levels of mental processing or physical activity are maintained or reduced.

The definition implies that psychological (experiential) and physiological aspects of fatigue need to be measured in order to understand the state of fatigue. In order to understand the fatigue *process*, we need in addition to characterise the form, dynamics and context of exertion, in addition to performance. The definition also accounts for sleepiness as a component of fatigue. The inclusion of exertion as a cause of increased homeostatic pressure in models of sleepiness explains the overlap between fatigue and sleepiness. Exertion in the face of homeostatic and circadian sleep pressure may also increase sleep propensity, and exacerbate the sleepiness component of fatigue. In fact fatigued states may be revealed in terms of performance decrements in circadian lows, as fatigue becomes too great for the operator to be able to compensate.

How to think about fatigue

Given that we wish to employ the broader concept of fatigue, how should we think about components that are not directly related to sleep drives, in particular those that are related to exertion, sustained activity, time at work and time on task? In particular, our thinking must be structured in a way that accounts for the large variation in time-on-task effects on performance. Two main models explain variation in time-on-task effects on performance by accounting for the nature of the task and/or the motivational influences on fatigue: the compensatory control model and the dynamic model of stress and attention. These models disagree fundamentally about whether the experience of fatigue is an indicator forecasting a future lack of energetic resources (mental or physical), or a discrepancy between the direction of actual behaviour and desired goals. We note that the latter makes it difficult to distinguish fatigue from stress, but it may be beneficial to consider that concerns about one's own physiological state *and* concerns about misalignment of behaviour and desires may contribute to the fatigued state and thus be limiting for performance. This approach can be assimilated into a new heuristic for the *process* of fatigue in human transport operators. This heuristic also accounts for sleep drives as an integral component of fatigue; the role of lower order (subconscious) and higher order (conscious) processes in determining performance; and the role of emotions and feelings linked to fatigue in determining fatigue effects on performance.

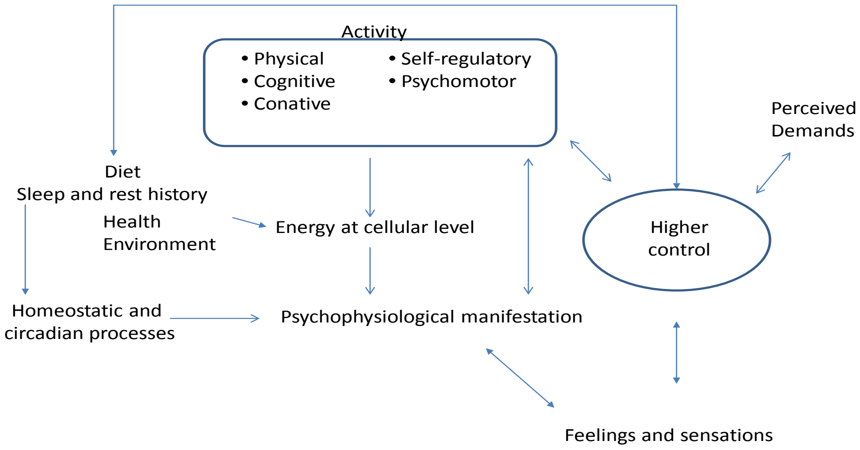

Figure S1. A holistic model of fatigue that accounts for the role of sleep. Here fatigue is not one step in the process, but is described by indices that map the system e.g. the collective state of experiential, physiological and performance/activity (physical, cognitive or psychomotor) indices.

Regardless of stance on the origin of the experience of fatigue, most authors agree that energetic limitations are not directly linked to performance decrements. In other words, when considering how fatigue affects performance, we must attend to the human transport operator's attitude and motivation he or she brings to the task. He or she will be adept at adapting to maintain performance, but that this has certain costs which any survey of fatigue should attempt to account for. These costs may be in terms of latent performance decrements and personal health or quality of life costs. When compensating for performance, we should also consider changes in strategy that an operator chooses to perform the task, and how these subtle changes may have implications for safety. Any survey should consider that some tasks, especially vigilance, may be inherently fatiguing in terms of performance.

Measuring fatigue

If fatigue is multidimensional, each dimension should ideally be surveyed when assessing fatigue in a sample, as far as this is practical. Self-reports are the most pragmatic way of gathering data, and this is important to consider when surveying human transport operators. Self-reports can be used not only to collect a measure of subjective fatigue states, but as a means of collecting performance data, or data on compensatory strategies, latent performance decrements or health effects. In assessing performance, it is important that reports relate specifically to performance of the task in question.

Most instruments have been developed to collect self-reports on acute subjective fatigue. A taxonomy of fatigue measures strongly suggests that chronic fatigue has been overlooked in the development of survey measures. Some instruments measuring acute fatigue measure exclusively sleepiness, while others tap into various aspects of the broader construct. After review, we conclude that instruments employing several items to assess each of several aspects of fatigue are preferable, and it is important that the instrument defines the period of interest for the respondent. Several popular scales are available, with good psychometric properties. Several scales analyse the experience of fatigue along several dimensions, the most common of which are physical, cognitive and emotional fatigue, and sleepiness. Each subdimension may map on to a general or overarching fatigue dimension. In addition to fatigue scales, scales developed independently to measure alertness should also be considered. Overall, we regard the Swedish Occupational Fatigue Index (SOFI) as promising for the measurement of fatigue experience in human transport operators. The SOFI is probably the most well developed scale for occupational fatigue, and different human transport operators may have characteristic subscale profiles, depending on the nature of their job. When assessing different workers we should remember that fatigue that is specifically task-related may be experienced along dimensions that are different from fatigue due to general tiredness and work, and it may be important to capture the task-specific fatigue experience in order to understand the most safety-relevant aspects of fatigue.

Objective measures tapping into the physiological state of fatigue have not yet been used to survey of large numbers of human transport operators. However, methods such as palmtop reaction time tests or actigraphy are becoming increasingly accessible, and may be worth considering. Alternatively it may be possible to survey representative subsamples of operators using objective methods. Again, measures of performance should be matched to safety-related performance of interest.

Safety performance effects of fatigue

Sleep deprivation has been found to affect a range of cognitive functions, most notably reaction time and lapses. Slowed and more variable reaction times are found in computer tests and real world driving. Functions affected by sleep deprivation that may be particularly relevant to human transport operators are reaction time, alertness, perceptual skills, decision making, judgments and cognitive slowing. Increased attention deficits and accelerated vigilance decrements may be particularly important. The implications of these functional decrements caused by sleep deprivation for performance will depend on the task or job activities in question. Monotonous, unstimulating tasks are more likely to make performance vulnerable to functional decrements. Time of day will also influence the extent of functional decrements and related performance outcomes. Importantly, sleep deprivation may produce impairments that reduces the ability of operators to handle unexpected, challenging situations, and make them more likely to rely on ingrained and inappropriate schemas. The fact that sleep deprived workers may also be more susceptible to distractions increases the likelihood of this happening.

Links have been established between recent sleep deprivation, circadian lows and accidents, implying the involvement of sleepiness. However, little is known about how chronic partial sleep deprivation, typical of real world working, affects performance, although we know that there are strong effects on attention and vigilance.

Isolating the effects of task fatigue on performance from the effects of homeostatic and circadian influences is often difficult and rarely achieved. However, there is good evidence that sustained task performance results in decrements to sustained attention and functions involved in vigilance, especially where the task is continuous, perceived as boring, is demanding or taxes attentional resources. In terms of real world settings, the following may induce task fatigue for human transport operators: driving on unstimulating, long straight roads; sailing a quiet ship on uneventful, open seas while following the same course; long straight, unstimulating rail stretches. These effects will of course be exacerbated by circadian nadirs and sleep deprivation. The job of human transport operator may also involve physically or other mentally demanding tasks that exacerbate vigilance performance decrements. Costs of attempting to maintain main task performance, include attentional narrowing, less use of memory, strain and effort, post-task preference for low effort, subjective fatigue and risky decision making. Thus the effects of fatigue on performance of the whole job may be important, as are interactions of other job characteristics, such as supervision levels, on performance. The effect of task-related fatigue on accidents and injuries is unresolved due to lack of suitable studies.

Specific effects on safety performance in human transport operators

Combined challenges of fatigue due to poor sleep history (especially irregular shift patterns and fragmented sleep), work at all times of day and sustained task performance appear to be the main influences on fatigue in human transport operators in the rail, road and sea sectors. In particular, all operators can be challenged by task underload, i.e. having to perform a vigilance task under unstimulating, monotonous conditions. This can occur at times of day when sleep drives are at their highest. Task overload may also be a particular problem for some operator roles. Thus a system of factors may interact to cause fatigue, and this system and the dynamic interaction of its elements that must be surveyed and managed to ensure that the performance and wellbeing of operators is not influenced unduly by fatigue.

The most serious effects of fatigue on transport operators are in terms of sleepiness and maintenance of cognitive task performance. For any operator, fatigue may pose a particular threat to skill-based task performance, in terms of increase risk of slips, lapses and mode errors. Fatigue-induced mode errors may be an overlooked threat and cause operators to persist with inappropriate strategies in unforeseen, deviant, demanding or distracting situations. Many fatigue-related safety problems may be caused by the influence of fatigue on complex faculties that allow operators to be mindful about emerging situations, assess a range of possibilities and act on emerging situations. In such cases fatigue will not only influence simple attention, but immediate priorities, expectations and the current world model, and access to and salience of knowledge and previous experience. Effects of fatigue on reaction time, decision-making and memory may also be important in this regard.

Implications for studying human transport operators

There are several implications for the study of fatigue in human transport operators:

- Fatigue should be operationalized using the provided definition, and thought about using the heuristic provided.
- Fatigue should ideally be measured in terms of the experience, physiological state and performance.
- The experience of fatigue itself should be measured along several dimensions, and supplemented with a measure of alertness.
- SOFI may be particularly useful, i.e. it is well developed and would allow for useful comparisons among different operators, and with other occupational samples.
- Cumulative chronic fatigue should not be ignored.
- Performance should be measured in a way that is specific to task-related safety.
- Motivational aspects surrounding the task or job should also be measured, and related to compensatory strategies, costs to the operator and latent performance decrements.
- Where there is a main safety-relevant task, the nature of the task itself should be considered.
- The physiological and behavioural methods of fatigue measurement may be difficult to apply in routine operations. In this regard, rapidly advancing handheld technology available to all (especially mobile phone apps) could be considered and/or study of a representative subsample.
- In regarding performance effects, the systemic interaction of sleep history, time of day and time at work or on task should be considered in the context of factors describing the operator’s job and non-work/off-duty life.
- For operators that may be sleep deprived, a range of cognitive functions may be challenged, and these may lead to reduced attention, poor detection abilities, vigilance problems, delayed response times, cognitive slowing, poor judgements and lapses; in particular there may be overreliance on ingrained schemas in deviant situations.
- For underloaded operators with task fatigue and little control, there may be problems with attention and vigilance.
- Job fatigue will also be associated with slips, lapses, mode errors and, again, the ability to assess and act appropriately in emerging situations that are non-routine.

Finally, when considering how to survey fatigue in human transport operators, we should consider that life outside work (or life off-duty) may also play an important role on fatigue while on duty. Constructs such as psychological detachment from work or work-life balance may be useful in this regard.

Sammendrag:

Hva er trøtthet og hvordan påvirker det sikkerhetskritisk atferd under framføring av transportmidler?

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Forfatter: Ross Owen Phillips
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Prioriteringen av trøtthet som en risikofaktor i transport er avhengig av en felles forståelse om trøtthet, om hvordan det bør måles, og om hvordan det påvirker sikkerhet. En felles forståelse kunne oppnås ved å anerkjenne trøtthet som et bredt begrep med ulike dimensjoner som bør måles, og som sammen beskriver erfaringsmessige aspekter, fysiologiske aspekter, og prestasjon. En slik tilnærming ville klargjøre aspekter av trøtthet som ulike studier ikke tar hensyn til. Det er også behov for økt overveielse av trøtthets langsiktige effekter hos den menneskelige operatøren. For å forstå hvordan trøtthet påvirker prestasjon, må vi ta hensyn til interaksjonene mellom søvn, døgnrytme og «time-on-task» i sammenheng med faktorer som beskriver ulike aspekter av livet, både innenfor og utenfor arbeid.

Det er en betydelig mangel på enighet om hva trøtthet er og hvordan det bør måles. Forskningslitteraturen er full av ulike forsøk på å operasjonalisere begrepet, og med mindre leseren forstår nøyaktig hvordan trøtthet har vært operasjonalisert i de ulike studiene, gir det liten mening å sammenligne forekomst på tvers av studier. Samsvarende operasjonaliseringer av trøtthet er nødvendig for mer konsistente målinger, for å muliggjøre sammenligning av resultater og for å styrke prioriteringen av trøtthet som en risikofaktor i transport i forhold til faktorer som lettere kan måles. Samsvar i begrepsbruken vil også hjelpe ledere til å forstå betydningen for trøtthet av at stadig større krav legges på arbeidstakere i et 24-timerssamfunn som øker i kompleksitet og krav til effektivitet. Denne rapporten tar sikte på å videreutvikle tidligere forsøk på operasjonalisering av trøtthetsbegrepet for bruk i forskning på menneskelige operatører i transport. Dette oppnås i hovedsak på to måter. For det første gjennomgås eksisterende definisjoner for å komme fram til en samlende definisjon for kartlegging av virkninger av trøttet på sikkerhetsrelaterte funksjoner. For det andre trekkes eksplisitte forbindelser mellom virkningene av trøtthet og de sikkerhetsrelaterte funksjonene.

Hva er trøtthet?

En viktig problemstilling når en skal operasjonalisere trøtthetsbegrepet er hvorvidt begrepet skal oppfattes som synonymt med *søvnighet*. Søvnighet er en tydelig og alvorlig trussel mot transportsikkerheten. Vi forstår søvnighet vesentlig bedre enn vi forstår andre komponenter ved trøtthet, både på operasjonelt, teoretisk og fysiologisk nivå. På grunnlag av søvnmengde og biologisk døgnrytme kan vi gjøre rimelig gode prediksjoner av gjennomsnittlig søvnighet for en gruppe operatører på ulike tidspunkter på døgnet, etter at de har fulgt et gitt arbeidstidsskjema. Et åpenbart spørsmål er hvorfor ikke heller fokusere på søvnighet som en sikkerhetsrisiko, og ignorere det forvirrende trøtthetsbegrepet helt? Det er flere svar. For det første ønsker vi å forstå virkningene av langvarig arbeid og det å arbeide i trøtt tilstand, og modeller for søvnighet sier lite om dette. For det andre kan operatører, selv om de ikke er søvnige, være trøtte slik at faktisk prestasjonsnivå eller evnen til å reagere i mulige uventede situasjoner reduseres. For det tredje er årvåkenhet en sentral oppgave for alle operatører i transport, og oppgaverelatert trøtthet kan ha sterk effekt på årvåkenhet. Og for det fjerde er vi interessert i å forklare hvordan akkumulert trøtthet knyttet til stress og lignende begreper kan føre til reduserte prestasjoner. Derfor vil vi operasjonalisere trøtthet som et bredt begrep som kan omfatte ikke bare virkningen av søvnighet på sikkerhet, men også oppgave- og jobbrelaterte virkninger, i tillegg til de mer langsiktig samspillseffekter mellom helse og sikkerhet.

En gjennomgang av eksisterende forsøk på definisjon viser at det bredere trøtthetsbegrepet ikke kan sammenfattes i én dimensjon, men har flerdimensjonale aspekter som er dynamisk sammenkoblet uten å være helt korrelert. Disse aspektene beskriver hvordan trøtthet manifesterer seg i subjektiv opplevelse, fysiologi og prestasjonsnivå. Virkningene av alle disse trøtthetskomponentene på operatøren må vurderes innenfor et systemperspektiv. Fra vår gjennomgang av litteraturen har vi utviklet en flerdimensjonal definisjon av trøtthet som er nyttig for å studere trøtthet hos operatører i transport, og andre forskere vil kunne ønske å benytte samme definisjon. Den er ment som en kontekstuell definisjon som kan legges til grunn for snevrere operasjonelle definisjoner til bruk i spesifikke studier av ulike aspekter ved trøtthet. Definisjonen er som følger:

Trøtthet er en suboptimal psykofysiologisk tilstand forårsaket av anstrengelse. Graden av og dimensjonene ved tilstanden avhenger av anstrengelsens form, dynamikk og kontekst. Anstrengelsens kontekst bestemmes av: Verdi og mening av prestasjon for personen i den aktuelle oppgaven, hvile- og søvnhistorikk, døgnrytme, psykososiale faktorer knyttet til arbeid og hjemmesituasjon, individuelle trekk, kosthold, helse, fysisk form og andre individuelle tilstander, og forhold i omgivelsene.

Definisjonen impliserer at psykologiske (opplevelsesrelaterte) og fysiologiske aspekter ved trøtthet må måles for at vi skal forstå tilstanden trøttet. For å forstå trøtthet som *prosess* må vi beskrive anstrengelsens form, dynamikk og kontekst i tillegg til prestasjonsnivået. Inkludering av anstrengelse som årsak til økt homeostatisk trykk i modeller for søvnighet forklarer overlapp mellom trøtthet og søvnighet. Anstrengelse på bakgrunn av homeostatisk og døgnrytmerelatert søvnighet kan også øke tendensen til å sovne, og forsterke søvnkomponenten ved trøtthet.

Hvordan bør vi tenke om trøtthet?

Gitt at vi ønsker å anvende et bredt trøtthetsbegrep, hvordan bør vi tenke om komponenter som ikke er direkte relatert til søvnbehov, spesielt de som er relatert til anstrengelse, vedvarende aktivitet, tid i arbeid, og hvor lenge en holder på med samme arbeidsoppgave? Tenkningen vår må spesielt struktureres på en måte som forklarer de store variasjonene i virkninger av oppgavens varighet («time on task», dvs. hvor lenge en holder på med én og samme arbeidsoppgave) på prestasjonsnivå. To modeller forklarer variasjon i virkninger av oppgavens varighet på prestasjonsnivået ved å redegjøre for betydningen for trøtthet av oppgavens art og personens motivasjon: «Kompensatorisk kontroll»-modell og «dynamisk modell for stress og emosjoner». Disse modellene skiller seg fundamentalt fra hverandre når det gjelder spørsmålet om opplevelsen av trøtthet er a) et forvarsel om kommende mangel på energiressurser (mentalt eller fysisk) eller b) en diskrepans mellom retningen på atferden og det ønskede målet. Den sistnevnte oppfatningen gjør det vanskelig å skjelne mellom trøtthet og stress. Likevel kan opptatthet av ens egen fysiologiske tilstand *og* av en diskrepans mellom atferd og ønsker bidra til trøtthetstilstanden og dermed bli en begrensende faktor for prestasjonen. Denne tilnærmingen kan inkorporeres i en ny forståelse av trøtthet som *prosess*. Denne forståelsen forklarer også søvnbehov som en integrert komponent i trøtthet, betydningen av underbevisste og bevisste prosesser for prestasjonsnivå, og betydningen av emosjoner og følelser knyttet til trøtthet for virkningen av trøtthet på prestasjonen.

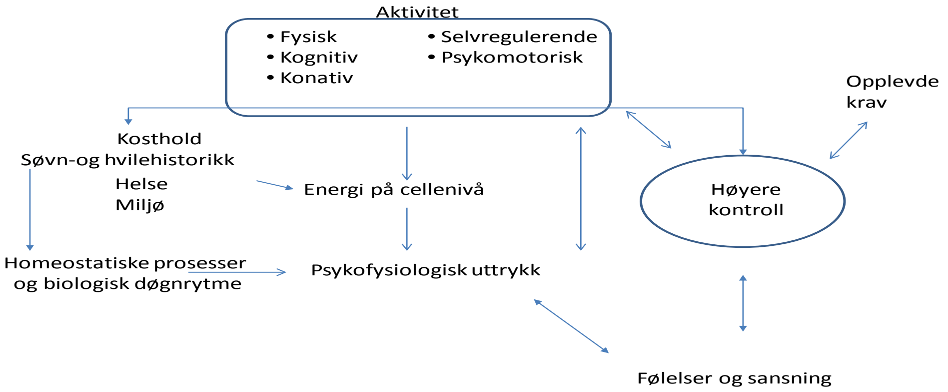

Figure S1. Helhetlig modell for trøtthet, som forklarer betydningen for søvn. Trøtthet er ikke en komponent i modellen, men beskrives ved indikatorer som refererer til ulike komponenter ved trøtthet som prosess, f.eks. av indikatorer på opplevelse, fysiologi og prestasjon/aktivitet (fysisk, kognitiv eller psykomotorisk).

Uansett standpunkt med hensyn til grunnlaget for opplevd trøtthet er de fleste forfattere enig i at energibegrensninger ikke er direkte knyttet til redusert prestasjon. Med andre ord, når vi tenker på hvordan trøtthet påvirker prestasjon, må vi være oppmerksomme på personens holdninger og motiver. Han eller hun vil kunne opprettholde prestasjonsnivået til tross for trøttheten, men det har kostnader som en kartlegging av trøtthet bør forsøke å gjøre rede for. Disse kostnadene kan dreie seg om latent reduksjon i prestasjonsnivået, eller redusert helse eller livskvalitet. Når vi undersøker hvordan personen kompenserer for trøtthet, bør vi også ta hensyn til endringer i de strategier personen velger for å utføre oppgaven, og hvordan disse subtile endringene kan påvirke sikkerheten. Enhver kartlegging bør ta i betraktning at noen oppgaver, særlig de som krever vedvarende årvåkenhet, i seg selv kan være trøtthetsskapende og føre til redusert prestasjon.

Måling av trøtthet

Dersom trøtthet betraktes som et flerdimensjonalt begrep, bør ideelt sett hver dimensjon måles når en undersøker trøtthet i et utvalg, så langt det er praktisk mulig. Selvrapport er den mest pragmatiske formen for datainnsamling, noe som er viktig å ta i betraktning når en undersøker trøtthet hos operatører i transport. Selvrapport kan benyttes ikke bare for å registrere subjektive trøtthetstilstander, men også for å registrere prestasjonsmål, eller data om kompensasjonsstrategier, latent prestasjonsreduksjon eller helseeffekter. Når en måler prestasjon, er det viktig at rapportene relateres spesifikt til den aktuelle oppgaven.

De fleste instrumenter for selvrapport er utviklet for å måle akutt subjektiv trøtthet. En taksonomi over mål på trøtthet tyder sterkt på at kronisk trøtthet er blitt oversett i utviklingen av måleinstrumenter for trøtthet. Noen instrumenter for å måle akutt trøtthet måler bare søvnighet, mens andre også fanger opp ulike aspekter ved det bredere trøtthetsbegrepet. Etter litteraturgjennomgangen konkluderer vi med at det er ønskelig med instrumenter som inneholder flere spørsmål for å måle hvert av de ulike aspektene ved trøtthet, og det er viktig at måleinstrumentet spesifiserer hvilken tidsperiode rapporteringen skal gjelde. Flere populære skalaer er tilgjengelige, med gode psykometriske egenskaper. Noen av dem analyserer opplevelsen av trøtthet langs flere dimensjoner, først og fremst fysisk, kognitiv og emosjonell trøtthet, og søvnighet. Dimensjonene kan kobles til én generell eller overgripende trøtthets-dimensjon. I tillegg til har det vært utviklet skalaer uavhengig av trøtthetsskalaene for å måle årvåkenhet. Skalaen Swedish Occupational Fatigue Index (SOFI) er et lovende instrument for å måle trøtthet hos operatører i transport. SOFI er sannsynligvis den best utviklede skalaen for trøtthet i arbeidssituasjoner, og ulike operatører kan ha karakteriske profiler for delskalaene, avhengig av hva slags jobb de har. Når en undersøker ulike grupper arbeidstakere bør en huske at trøtthet spesifikt relatert til arbeidsoppgaven kan oppleves langs andre dimensjoner enn trøtthet som skyldes generell slitenhet og arbeid, og det kan være viktig å fange opp opplevelsen av oppgavespesifikk trøtthet for å forstå de mest sikkerhetsrelevante aspektene ved trøtthet.

Objektive fysiologiske målinger av trøtthet har ennå ikke blitt benyttet i kartlegging av store grupper operatører i transport. Imidlertid er metoder for å måle reaksjonstid ved hjelp av apper til smarttelefon blitt stadig lettere tilgjengelige, samt aktigrafer for å måle både søvnmengde og fysisk aktivitet, og slike instrumenter kan være aktuelle i kartleggingsprosjekter. Alternativt kan det være mulig å undersøke representative underutvalg av operatører med objektive metoder. Igjen må det understrekes at mål på prestasjon må knyttes til de sikkerhetsrelaterte oppgavene en er interessert i.

Virkning av trøtthet på sikkerhetskritisk atferd

Søvndeprivasjon har vist seg å påvirke en rekke kognitive funksjoner, særlig reaksjonstid og feil handlingsvalg. Forlengede og mer variable reaksjonstider er påvist i computertester og under bilkjøring. Funksjoner som er påvirket av søvndeprivasjon og som samtidig er særlig relevante for operatører i transport, er reaksjonstid, årvåkenhet, perseptuelle ferdigheter, beslutningstaking, vurderingsevne og kognitiv hastighet. Oppmerksomhetssvikt og stadig mer redusert årvåkenhet er særlig viktig. Implikasjonene av disse funksjonsforstyrrelsene for prestasjonsnivået avhenger av den aktuelle oppgaven eller aktiviteten operatøren holder på med. Monotone og lite stimulerende oppgaver bidrar sannsynligvis til å gjøre prestasjonen mer sårbar for nedsatt funksjonsnivå. Tid på dagen påvirker også graden av nedsatt funksjonsnivå og prestasjon. Særlig viktig er det at søvndeprivasjon fører til svekkelser som reduserer operatørenes evne til å reagere på uventede utfordringer, og gjør dem mer tilbøyelig til å ty til innarbeidede kognitive skjemaer, som ikke nødvendigvis er adekvate for situasjonen. Dette problemet forsterkes av det faktum at søvndepriverte arbeidere også er mer utsatt for distraksjoner.

Det er påvist sammenhenger mellom nylig søvndeprivasjon, bølgedaler i den biologiske døgnrytmen og ulykker, noe som viser betydningen av søvnighet. Men en vet lite om hvordan delvis søvndeprivasjon over lengre tid, som er et ofte forekommende problem, påvirker prestasjonsnivået, bortsett fra sterke effekter på oppmerksomhet og årvåkenhet.

Det er ofte vanskelig å isolere virkningene av oppgaverelatert trøtthet på prestasjonsnivå fra homeostatiske effekter og effekter av tid på døgnet. Det er imidlertid sterk evidens for at langvarig arbeid med samme oppgave fører til reduksjon av vedvarende oppmerksomhet og funksjoner relatert til årvåkenhet, særlig dersom oppgaven er kontinuerlig, oppfattes som kjedelig, er oppmerksomhetskrevende eller krevende på andre måter. I virkelige arbeidssituasjoner kan følgende forhold medføre oppgaverelatert trøtthet hos operatører i transport: kjøring på lite stimulerende lange, rette strekninger; føre et stille skip på fast kurs på åpent hav; lange, rette og lite stimulerende jernbanestrekninger. Disse effektene forsterkes selvsagt av bølgedaler i døgnrytmen og av søvndeprivasjon. Arbeidet til en operatør i transport kan også medføre andre mentalt krevende, eller også fysisk krevende, oppgaver som ytterligere reduserer årvåkenheten. Kostnadene knyttet til anstrengelsen med å opprettholde prestasjonsnivået omfatter innsnevret oppmerksomhet, følelse av stress, behov for redusert anstrengelse etter oppgaven, subjektiv opplevelse av trøtthet, og risikopregede beslutninger. Dermed kan virkninger av trøtthet på hele jobbsituasjonen bli viktig. Virkningen av oppgaverelatert trøtthet på ulykker og skader er lite kjent fordi det mangler adekvate studier.

Spesifikke virkninger for operatører i transport

Kombinasjonen av mangelfull søvnkvalitet/-mengde (særlig uregelmessige skiftordninger og oppstykket søvn), arbeid på «feil» tid på døgnet, og vedvarende arbeid med samme oppgave ser ut til å være hovedårsaken til trøtthet hos operatører innenfor både bane, vei og sjø. Først og fremst kan understimulering være et problem for alle operatørene, dvs. å utføre en oppgave som krever årvåkenhet under monotone forhold. Dette kan skje på tidspunkter på døgnet hvor søvnbehovet er størst. Overbelastning kan også være et problem i enkelte operatørjobber. Følgelig er det et system av faktorer som spiller sammen i å generere trøtthet, og dette systemet og det dynamiske samspillet mellom dets elementer må overvåkes og kontrolleres for å sikre at operatørenes prestasjonsnivå og velvære ikke blir negativt påvirket av trøtthet.

De alvorligste utfordringene når det gjelder trøtthet hos operatører i transport gjelder søvnighet og opprettholdelse av prestasjonsnivå ved kognitive oppgaver. For enhver operatør kan trøtthet være en trussel når det gjelder utføring av ferdighetsbaserte oppgaver, ved at trøttheten øker risikoen for feilhandlinger og feilvurderinger. Feilvurderinger kan være en undervurdert trussel som kan få operatører til å bruke inadekvate strategier i uforutsette, avvikende, krevende eller distraherende situasjoner. Mange trøtthetsrelaterte sikkerhetsproblemer kan være forårsaket av at trøttheten hemmer komplekse ferdigheter som bidrar til at operatørene er konsentrert om situasjoner som dukker opp, vurderer mange alternative muligheter og handler adekvat. I slike tilfeller vil trøttheten ikke bare påvirke enkel oppmerksomhet, men umiddelbare prioriteringer, forventninger og situasjonsforståelse, samt evne til å bruke kunnskap og tidligere erfaringer. Virkningene av trøtthet på reaksjonstid, beslutningstaking og hukommelse kan også være viktige her.

Implikasjoner for undersøkelser av operatører i transport

Det er flere implikasjoner for undersøkelser av menneskelige operatører i transport:

- Trøtthet bør operasjonaliseres og forstås/forklares i henhold til en bred definisjon og begrepsapparat, slik som det er foreslått her.
- Trøtthet bør ideelt måles ut fra opplevelse, fysiologisk tilstand og prestasjon.
- Selve opplevelsen av trøtthet bør måles langs flere dimensjoner, og suppleres med et mål på våkenhet.
- SOFI er et særlig nyttig verktøy; dvs. det er godt utviklet og vil muliggjøre nyttige sammenligninger mellom forskjellige operatører og med andre utvalg.
- Kumulativ kronisk trøtthet må ikke undervurderes.
- Motivasjonelle aspekter ved oppgaven eller jobben bør også måles, og relateres til kompensasjonsstrategier, belastning for operatøren og latente reduksjoner i prestasjonsnivå.
- Fysiologiske og atferdsbaserte metoder for å måle trøtthet kan være vanskelig å anvende i en arbeidssituasjon. Smarttelefon-applikasjoner eller annen lett tilgjengelig håndholdt teknologi kan vurderes, og/eller undersøkelse av et representativt underutvalg.
- Når det gjelder virkninger på prestasjon, bør systemsamspillet mellom søvnhistorikk, tid på dagen og varighet av oppgaven eller jobben vurderes sammen med andre faktorer som kjennetegner operatørens jobb- og fritidssituasjon.
- For operatører som kan være søvndepriverte, kan en rekke ulike kognitive funksjoner være berørt, og disse kan føre til redusert oppmerksomhet, dårlig oppfattelse, redusert årvåkenhet, økt reaksjonstid, kognitiv treghet, dårlig vurderingsevne, og feilhandlinger. Spesielt kan det forekomme at en stoler for mye på etablerte tanke- og handlingsmønstre i avvikssituasjoner.
- For understimulerte operatører med oppgaverelatert trøtthet og lav kontroll kan det oppstå problemer med oppmerksomhet og årvåkenhet.
- Arbeidsrelatert trøtthet er også forbundet med feilvurderinger og feilhandlinger, som vil påvirke evnen til adekvate vurderinger og handlinger i situasjoner som ikke er rutinemessige.

Til slutt, når en skal vurdere hvordan trøtthet hos operatører i transport bør undersøkes, bør en ta i betraktning at livet utenom jobben også spiller en viktig rolle for trøtthet i arbeidssituasjonen. Begreper som psykologisk frikobling fra jobben og balanse mellom arbeid og fritid er viktige i denne vurderingen.

1 Background

The need for this report arose from an initial meeting of a Reference Group for the project Fatigue in Transport (FiT), part of the Norwegian Research Council's TRANSIKK program. The aim of the project is to increase what we know about the fatigue status of human operators working in different transport sectors in Norway, in order to assess whether there is a need for fatigue management by transport organisations.

During an initial meeting of the project's Reference Group it became clear that the concepts "tiredness", "sleepiness" and "fatigue" were pervasively confounded both in everyday language and in research and measurement. At the same time it was pointed out that the project would need to address a fundamental problem, that the effects of fatigue depend on how it is measured, and how it is measured depends on how it is modelled and defined. As a result of this meeting, some project resources were devoted to consider how fatigue has been approached and operationalized by other researchers, and which approach was most relevant when considering how fatigue affects the safety-related functions of human transport operators.

The present report conveys our particular and selective understanding of the concept of fatigue as it relates to safety-related functions of the human transport operator. It is effectively a position paper which underpins our approach to the rest of the project, and hence our eventual findings. Although the literature on fatigue is vast, we found that there was a lack of attempts in *applied* research to explicitly justify how fatigue is thought about and measured. By providing an overview of aspects to consider when operationalizing fatigue, this report will help practitioners prepare for research and any associated interventions. It will also be useful to anyone else who wants to assess the fatigue status of employees in an organization.

Managers responsible for the safety of human transport operators may only have considered fatigue indirectly, as part of their obligations under working hours legislation. They may not have understood the different ways fatigue can manifest itself, or may not have considered the need to operationalize, measure and, where necessary, monitor and control fatigue. This report will be of interest to them, as well as to relevant work authorities, to whom it explains the need to control different aspects of fatigue.

While transport researchers will recognize the problem of fatigue, they might have found it difficult, as we did, to get an overview of the wealth of research on this issue, which spans several research domains. Not all researchers will have considered how fatigue differs from sleepiness, or how these two concepts combine to affect operator performance. They may not have considered factors causing different manifestations of fatigue and how these have been modeled and described. We hope that the report will also provide useful explanations to them.

In summary, our hope is that this report outlines and justifies the approach to fatigue taken in the FiT project, while at the same time providing background research on fatigue in a way that will be useful to managers, authorities and researchers.

The report does not review applied research studies that have attempted to assess and control fatigue in human transport operators. Rather, these studies will be the subject of a separate report by the FiT project.

2 Introduction

According to reviews of international research the prevalence of safety-relevant fatigue in various populations has been reported as between 5 and 45 per cent (Chen, 1986; Ho et al., 2013; Loge et al., 1998; Åhsberg, 1998). In working populations a fatigue prevalence of 20 per cent has been reported (Bültmann et al., 2002; Kant et al., 2003).

While these figures give some idea of the commonality of fatigue, they disguise a long-standing lack of consensus among fatigue studies, about what fatigue is or how it should be measured (Bartley & Chute, 1947). The literature is peppered with divergent attempts to operationalize the term, and unless the reader understands precisely how fatigue has been operationalized in the different studies, a comparison of prevalence rates is almost meaningless. While some authors define fatigue explicitly for respondents, often using narrow or rarely used definitions, others let respondents to define the term for themselves (Hanowski et al., 2011; Williamson & Friswell, 2013). The problem with the latter is that respondents seem to find it hard to distinguish fatigue from other experiential concepts with which fatigue co-occurs, and researchers cannot be sure how much they are also tapping into other constructs, such as stress (Tepas & Price, 2000), anxiety (Lal & Craig, 2001), burnout (Huibers et al., 2003) or boredom (Scerbo, 2000). These problems are long-standing, as are claims that the term “fatigue” should be dismissed from scientific study (Muscio, 1921 cited in Åhsberg, 1998). It has even been claimed more recently that fatigue should be absorbed into the study of emotion (Stokes & Kite, 2000).

It seems fair to say, however, that there are increasing reasons to dismiss such claims. Considerable progress has been made in understanding specific aspects of fatigue, such as sleepiness (Åkerstedt et al., 2004) or the effect of specific types of sustained performance on cognitive function (Ackerman, 2011). Rapid progress has been made recently in understanding the neurology of fatigue (Matthews et al., 2012). Such progress has helped solidify the concept of fatigue, and supports that it is meaningful and useful (Åhsberg, 1998). There is also increasing acceptance that the numerous attempts at definition appearing in the literature may each have something to contribute to the overarching concept, which is increasingly seen as diffuse and multidimensional, with increasingly important implications for health and safety (Phillips & Sagberg, 2010a).

The need for managers to understand and tackle fatigue is also greater than ever as more demands are placed on workers in a 24-hour society increasing in complexity and efficiency (Ho et al., 2013; Lützhöft et al., 2007; Ricci et al., 2007; Strober & Deluca, 2013; Åkersted, 2000). The inability of researchers to concretely identify what most agree is an important concept in occupational health and safety, does not necessarily prevent its management by inference, as is evidenced by widespread organisational programs for the management of the related concept stress (Cooper & Cartwright, 2000) and an increasing number of programs to manage fatigue itself (Phillips & Sagberg, 2010a). While pragmatic progress is encouraging, it would be greatly assisted and enhanced by addressing the methodological uncertainties found in the literature (Hartley & Arnold, 2000). Greater convergence on operationalization would lead to consistency of measurement, allow comparisons across findings, and increase the priority of fatigue as a causal factor in relation to those causes that are more easily measured (Brown, 1995).

This report seeks to generate a consensus definition for the study of the effect of fatigue on safety-related functions of human transport operators through reviewing existing attempts at definition. A particular concern was to avoid narrowing our consideration of fatigue to a single element, such as sleepiness or time on task, since we believed that understanding the broader concept of fatigue as it exists and affects behaviour is necessary for the subsequent design of optimally effective interventions.

Three questions need to be asked before beginning to survey the fatigue status in any group of people. These are:
1. What is the most useful definition of fatigue for this group?
2. Which fatigue measures are most valid for the assessment of fatigue in this group?
3. Which effects of fatigue are most important to measure for this group?

By guiding the reader through the array of definitions, dimensions and models that we considered in order to answer these questions for the case of the human transport operator, we hope to make explicit those decisions to be made by anyone wanting to survey and tackle fatigue.

We found our answers using a literature review, the strategy of which was as follows:

- Review ways fatigue has been operationalized (defined and modeled), and what that says about how fatigue should be measured.
- Consider how the effects of fatigue can be measured, and what those effects have been found to be.
- Review safety-relevant functions of human transport operators.
- Consider an appropriate operationalization of fatigue in relation to safety in human transport operators.
- Draw links between the effects of fatigue and safe safety functions of human transport operators.

Note that this review is structured to help answer the three questions above. In particular, identifying an appropriate operationalization of fatigue in relation to the safety functions of human transport operators addresses what is the most useful definition and measures of fatigue in our case. By drawing links between the effects of fatigue and safety-relevant functions of human transport operators, we will address which effects will be the most important to measure.

The next chapter, Chapter 3, briefly states the aims of this report. Chapter 4 reviews and draws conclusions about how to define fatigue, while Chapter 5 considers how we should think about and model the construct in relation to others. Chapter 6 describes approaches to its measurement. In Chapter 7 we consider the effect of fatigue on general performance. Chapter 8 briefly sets out the job contexts and safety-relevant aspects of human transport operators in road, sea and rail; and also describes findings on the links between fatigue and performance for these cases. Finally, in Chapter 9 we draw conclusions about how to operationalize fatigue in order to map, study and tackle it effectively in the case of human transport operators.

3 Aim

The primary aim of this report is to inform the reader about how fatigue in transport operators can best be surveyed in relation to its effects on the safety-related functions of human transport operators.

Its secondary aims are to provide an account of:

- How fatigue has been defined in the literature
- How fatigue has been modeled
- How fatigue has been measured
- Safety-related functions of human transport operators
- Links between fatigue and safety-related functions of human transport operators

The focus of the report is human transport operators in the rail, road or sea sectors, internationally and, where there is relevant research, in Norway.

4 How should we define fatigue?

4.1 Everyday usage

When researchers survey or talk to people about a concept in order to measure it, they often aim to optimize the face validity[1] of their research by using an operational definition that reflects everyday usage.

According to English dictionaries, fatigue in humans is “extreme tiredness arising from mental or physical effort” (Oxford Dictionaries, 2013). A comparison with definitions for tiredness (“a need for sleep or rest”) and sleepiness (“the state of being sleepy”) shows that fatigue is unique in the way it is ascribed a cause, namely exertion (Oxford Dictionaries, 2013). Furthermore, while sleep is presumably the main way to recover from sleepiness[2], it is not clear from the dictionary definition whether sleep or rest is required to recover from fatigue. We might also add that according to dictionary definitions, sleepiness may or may not occur in association with fatigue (Apostolopoulos et al., 2010).

It is important to question the assumption that dictionary definitions actually reflect everyday usage, which often sees unclear use of terms like sleepiness, tiredness and fatigue. Certainly our own unpublished research finds that people seem to have trouble verbalizing the difference between fatigue and general tiredness. On the other hand use of the word in everyday language in phrases like “metal fatigue” or “battle fatigue” do seem to reflect dictionary definitions in that someone or something is “tired” to the extreme specifically because of some overuse, overexposure or exertion.

4.2 Fatigue as an experience

Several definitions in the research literature are closely related to dictionary definitions in that fatigue is described as a subjective feeling, experience, sense or awareness that arises from exertion (Table 1).

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[1] Extent to which a construct appears to measure what it purports to measure, according to respondents.

[2] Circadian effects notwithstanding.

Table 1. Different definitions of fatigue grouped according to type.

Category	Example	Source
Dictionary	"…extreme tiredness resulting from mental or physical exertion or illness."	Oxford Dictionaries (2013)
Subjective	"feeling tired, sleepy or exhausted."	(NASA, 1996), cited in (Soames-Job & Dalziel, 2000)
	"subjectively experienced disinclination to continue performing the task because of perceived reductions in efficiency."	(Brown, 1995)
	"an overwhelming sense of tiredness, lack of energy and a feeling of exhaustion, associated with impaired physical and/or cognitive functioning"	Shen et al., (2006)
	"awareness of a decreased capacity for physical and/or mental activity due to inbalance in the availability, use and/or restoration of resources needed to perform an activity."	(Aaronson et al., 1999), cited in (Strober & Deluca, 2013)
Physiological	" the state of an organism's muscles, viscera, or CNS, in which prior physical activity and/or mental processing, in the absence of sufficient rest, results in insufficient cellular capacity or system-wide energy to maintain the original level of activity and/or processing by using normal resources.	(Soames-Job & Dalziel, 2000)
	"weakness…from repeated exertion or a decreased response of cells, tissues, or organs after excessive stimulation, stress or activity."	(Hirshkowitz, 2013)
	...a change in psychophysiological state due to sustained performance [of one or more tasks at work]	(van der Linden et al., 2003)
Physiological/performance	"reduced force production, loss of exercise capacity, increased sense of effort or perception of force"	(Davis & Walsh, 2010)
	"…is the inability to function at the desired level due to incomplete recovery from demands of prior work and other waking activities. Acute fatigue can occur when there is inadequate time to rest and recover from a work period. Cumulative or chronic fatigue occurs when there is insufficient recovery from acute fatigue over time."	(Gander et al., 2010)
Performance	"measurable decrements in performance of an activity caused by extended time performing it"	(Bartlett, 1953), in (Gawron et al., 2000)
	"a diminished capacity for work and possibly decrements in attention, perception, decision making and skill performance"	(Cercarelli & Ryan, 1996)
	"decrements in performance on tasks requiring alertness and the manipulation and retrieval of information stored in the memory"	(Gawron et al., 2000)
Multiple	"There are three aspects to fatigue: physiological, objective (work decrement), and subjective fatigue."	(Bills, 1934)
	"an individual's multi-dimensional physiological-cognitive state associated with stimulus repetition which results in a prolonged residence beyond a zone of performance comfort."	(Hancock & Verwer, 1997)
	A psychophysiological state that occurs when a person is driving and feeling tired or drowsy, to the extent that they have reduced capacity to function, resulting in performance decrements and negative emotions and boredom as they attempt to stay awake during the task.	(Craig et al., 2011)

These subjective definitions are supported by claims that we cannot ignore the experiential aspects of fatigue without losing its essence and detaching it from its originally intended and actual usage (Bartley & Chute, 1947; Brown, 1995). A typical counterclaim is that defining fatigue by anchoring it to our varying personal experiences of reality is unscientific, and will inevitably result in contextually and culturally dependent measures (Mosso, 1904 cited in Strober & Deluca, 2013). Others point out the falseness of defining fatigue as an experience, because it is an emergent and ephemeral property of consciousness, “underwritten by the interaction of multidimensional factors of both an environmental and a neurophysiological nature”, and which is only accorded illusionary unitary status by the unity of consciousness itself (Strober & Deluca, 2013; Desmond & Hancock, 2001). For some authors such contentions are supported by the failure of recent work in neuroscience to reveal anything about the subjective experience of fatigue.

A further problem with definitions that are exclusively experiential is that there appears to be a complex non-linear relationship between subjective fatigue and its effects on performance (Jobs, 2000), although, as we shall see, this may be because people compensate to maintain performance. What is true, however, is that heavily-fatigued people seem to become too fatigued to recognize that they are fatigued, such that the severity of the most important cases of fatigue may be underestimated by self-reports.

Finally, experiential definitions have become associated with attempts to reserve the term “fatigue” for extreme tiredness caused by mental exertion, and “impairment” for that caused by physical exertion (Brown, 2000). The usefulness of this distinction is questioned given that (i) many jobs include a mixture of physical and mental tasks that lead to a general feeling of fatigue, and (ii) that there are somatic influences on mental tiredness (Domasio, 1994). Indeed, authors have recently pointed to the possibility of a common physiological basis for mental and physical fatigue: “as the muscle is the organ of physical action, so the brain is the organ of cognitive action and each [depends on limited energy stores and] similar response strategies” (Hancock et al., 2012).

Three points are worth making before leaving our discussion of experiential definitions of fatigue.

1. While there are (i) many useful and important concepts with a central subjective and thus intangible aspect, e.g. stress, and (ii) important effects of subjective fatigue other than on short-term performance (e.g. health, performance effects that build up over time), there are really no robust arguments against a definition of fatigue whose description includes an experiential aspect, particularly given the importance of the latter for face validity.
2. While it may be interesting to distinguish between feelings of physiological and mental fatigue, it may not be necessary, and indeed it may be unnatural, to force respondents to make this distinction. In other words, what may be most interesting in terms of its implications for work-related behaviour and health is the summative feeling of exhaustion.
3. We find no clear argument for why a definition of fatigue should be *exclusively* subjective, especially when “[physiological and performance] measures can provide useful information on the nature, validity and reliability of fatigue as experienced by the individual” (Brown, 2000).

4.3 Fatigue as a physiological condition

The difficulties of operationalizing fatigue as an experience has made several authors turn away from everyday usage of the phrase, towards definition of fatigue as a physiological state of weakness or depletion resulting from activity (Table 1).

One advantage of this approach is that as researchers start to elucidate the neurophysiological mechanisms of fatigue, framework physiological definitions may be "filled in" (Soames-Job & Dalziel, 2000). Thus, while the essence of the definitions would remain unchanged, they would become more detailed and accurate as our knowledge increased. For example, the "state" described by Soames-Job & Daniel's (2000) physiological definition (see Table 1) would be more accurately described in future definitions.

There are two important criticisms of this approach, however.

The first is that while we are finding out more about the neurological processes underpinning fatigue, we are still a long way off understanding the precise physiological mechanisms responsible for fatigue, or even how many different mechanisms there are. Thus there is no biochemical test for fatigue in sight; indeed fatigue is likely to be the summative result of different biochemical and psychophysiological mechanisms (e.g. glucose depletion, sleepiness, boredom). As at the experiential level, we are at the physiological level still attempting to define a phenomenon. We may therefore be justified in thinking that an experiential definition is more appropriate and useful in terms of measuring effects on human transport operators, since at least such definitions have better face validity.

The second criticism of a physiological definition of fatigue is that as soon as we move away from experiential definitions, we lose an essential aspect of fatigue, which is related to the importance of psychological processes in relation to performance. People almost never reach their energetic limitations, due to the importance of motivational processes, i.e. we might never be able to understand and explain fatigue solely in terms of the physiological depletion of energy processes (Bartley & Chute, 1947).

4.4 Fatigue as performance decrement

A further way in which fatigue has been defined is in terms of its effects on performance output (Table 1). Such definitions may seem especially relevant to safety managers, who are concerned about the effects of fatigue on safety-relevant functions of the human transport operator.

The criticism that we cannot explain the effects of fatigue without reference to its psychological aspects, also applies to attempts to define fatigue in terms of performance output. No matter how interested we may be in performance, to ignore how people experience fatigue is likely to limit our understanding. As we have already indicated, for some cognitive tasks there is a non-linear relationship between subjective fatigue and its effects on performance (Bruce et al., 2010; May, 2011; Saxby et al., 2013). Despite increased reports of fatigue in prolonged driving tasks, the effects on safety performance are described as surprisingly weak even after 11 hours of driving (Hamelin, 1987; Strober & Deluca, 2013). It seems we can maintain some aspects of cognitive performance even when we are fatigued, for instance by increasing exertion, with the result that there is no detectable effect on performance. Thus when measured solely in terms of performance, the covert costs of fatigue to the operator go undetected (Hockey, 1997). While these costs may themselves cause fatigue and be detrimental to safety performance and operator health in the longer term, this does not seem satisfactory (Brown, 1995; Fairclough, 2000).

The importance of psychology in understanding fatigue-related performance is well illustrated by new research, which shows that participants who are led to believe that they have slept better than they actually have, perform better at a test of mental cognition than those who are led to believe that they have slept worse (Draganich & Erdal, 2014).

4.5 Fatigue as a multidimensional construct

To summarise the discussion so far, we have discussed that the experience of fatigue is central to operationalizing of fatigue, in that it allows for face validity, and is necessary for a complete understanding of the performance effects of fatigue. We have also said that there is no reason why any definition should be exclusively experiential, and given good reasons to include physiological state and performance aspects when operationalizing fatigue. Thus fatigue may best be defined as a multidimensional construct.

Researchers who have attempted to define fatigue by emphasizing one particular aspect (experience, physiology or performance) have described only a limited part of a larger, multifaceted concept. These attempts have inevitably led to definitions that are seen as unsatisfactory or incomplete by researchers interested in other or multiple aspects of fatigue.

The problems of definitions of fatigue based on selected dimensions are highlighted by studies showing dissociation between physiological and subjective measures of fatigue during sustained vigilance tasks, where individuals report increased mental effort even though physiological (heart rate variability) measurements indicate decreased mental effort (Verwey & Zaidel, 2000). Other driver simulator studies also show dissociation between physiological measures (video analysis of blink rate, yawns etc) and psychological measures (self-reports before and after driver simulation event) (Craig et al., 2011). Moreover, the best predictor of performance has been found to be a weighted combination of physiological and psychological measurements[3].

Objections that fatigue is experienced artificially by the mind as unitary also suggest that, as it is a complex and dynamic psychophysiological state, fatigue should be assessed using a range of outcome measures. Multidimensional measurement of fatigue may also help understand its dynamics. In early stages of the fatigue process, measurements based on subjective definitions may be the best and indeed only way

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[3] Such findings have led to the proposal that information processing involves two hierarchically ordered levels, in which the upper executive level controls the lower level automatic processes. The hypothesis is that the upper level processes are indexed by subjective experience of mental effort, while the lower level processes are those measured by physiological indicators. This supports early findings that physical performance deterioration, presumably tracked by physiological deterioration, was not necessarily associated with the subjective experience of fatigue (Bartley & Chute, 1947).

to capture of fatigue, in terms of its cost to the operator of maintaining performance (at least in real world situations). In later stages, measurements based on performance definitions would appear to become more important as performance is increasingly affected.

Recently, long-standing authors in the field maintained that a physiological basis for definition (*"a lack of sufficient steady state energy to power physical and/or cognitive work)"* would suffice as long as there are certain caveats (Hancock et al., 2012). These are (i) that fatigue is encountered as a "subjective apperception of self-state" triggered by the insufficiency of steady state energy, and is thus susceptible to all the nuances and subtleties of individual differences (thus people respond differently to the same objective demands); and (ii) that the individual can ignore perception of fatigue, depending on goals and task appraisals. In our view, this approach is not inconsistent with the idea that fatigue would be best understood and operationalized by considering its physiological, experiential and performance dimensions.

Reflecting these arguments, a triad of bodily, performance and perceptual aspects for fatigue is increasingly accepted, not least by those wishing to understand and tackle fatigue in order to improve occupational safety (Bartley & Chute, 1947; Matthews et al., 2012; Åhsberg, 1998). Calls for a multidimensional definition have also been echoed by clinicians (Shen et al., 2006), and are also evident in influential treatments of fatigue (Grandjean, 1979). Indeed several multidimensional definitions of fatigue are also now available (e.g. Table 1), although these have limitations as we will now describe.

4.6 Definition for the study of fatigue in human transport operators

We have argued that a multidimensional definition of fatigue is required for the study of fatigue in human transport operators. Of the definitions in Table 1, Soames-Job & Dalziel's (2000) definition is a more preferable starting point than those multidimensional definitions listed. We give the following reasons for this, along with ways in which Soames-Job and Dalziel's definition may be improved further, in terms of evolving a broad multidimensional definition of fatigue.

- Unlike Craig et al.'s (2011) definition, it explains the cause of fatigue – it doesn't just "occur" (Table 1). Soames et al. (2000)'s definition also appears preferable to Hancock and Verwer's (1997) in that it widens the cause from stimulus repetition to account for fatigue-inducing activities that are less task specific, like decision making or repetition of behaviour.
- It allows physical and mental activity to be included as causes. We regard the inclusion of both mental processing and physical activity as important causes of fatigue for human transport operators. Even where there is not physically demanding activity, such as when monitoring, staying in a fixed position is physically demanding, and even regulation of breathing during monitoring requires considerable energy. However we note that physical and mental activity can be implied by the term "exertion", which we define as "mental processing or physical performance requiring directed effort".
- "The absence of sufficient rest" in Soames-Job and Dalziel's (2000) definition allows for rest or sleep periods during a variety of tasks that can last for hours,

days or weeks. Thus a range of activities, as can occur within single jobs, is accounted for as a cause of fatigue, and not just single tasks. For example, truck drivers have to load lorries as well as drive for hours on end, and the vigilance tasks of sea officers are interspersed by split shifts, paperwork or even physical labour during port calls (see Section 7). However, fatigue can also occur due to exertion in the face of other factors other than lack of rest or sleep. Several studies show how health status, health habits and food intake influence subjective fatigue and performance (Taylor & Dorn, 2005), and how individual differences, the external environment, conflicting intrinsic goals and psychosocial influences also affect the level of fatigue present in the workplace (Bakker et al., 2005; Hockey, 2010; Waterhouse, 2012). Each of these factors may contribute to the level of fatigue in transport operators.

- Soames-Job and Dalziel's (2000) definition allows for the original level of activity to be reduced or maintained using adaptive strategies, accounting for possible disconnect between subjective fatigue and performance effects.

While Soames-Job and Dalziel's (2000) definition may be seen by some as accounting for experiential aspects as the experience of the deconditioned state of the "muscles, viscera or CNS". However, we doubt whether the psychological experience of fatigue will ever be able to be directly related to its physiological basis, since it will be influenced by abstract concepts such as consciousness, attention, and competing goal-based activity. Given the importance of subjective fatigue in controlling energetic output, we contend that Soames' definition would be usefully modified by accounting for experiential aspect of fatigue. This may be done by considering fatigue as a psychophysiological condition, with intractable psychological and physiological aspects.

Fatigue is a suboptimal psychophysiological condition caused by exertion. The degree and dimensional character of the condition depends on the form, dynamics and context of exertion. The context of exertion is described by the value and meaning of performance to the individual; rest and sleep history; circadian effects; psychosocial factors spanning work and home life; individual traits; diet; health, fitness and other individual states; and environmental conditions. The fatigue condition results in changes in strategies or resource use such that original levels of mental processing or physical activity are maintained or reduced.

The above definition accounts for the cause of fatigue, as exertion, as well as the experiential, physiological and performance facets of the construct. The definition implies that we should measure two aspects of the psychophysiological condition of fatigue. Firstly, its degree relative to an optimal subjective or objective state, where an optimal state is one found in a fully recovered, rested and healthy individual, or the average for a group of fully recovered, rested and healthy individuals. Secondly, its dimensional character in terms of psychological and physiological dimensions and their respective subdimensions. Examples of psychological subdimensions are cognitive, conative, affective, self-regulatory experiences, and sleepiness. Examples of physiological subdimensions are biochemical indicators, outwardly observable effects of fatigue such as facial tone, and various changes in electropotentials. The definition also implies that fatigue is a condition best understood by considering in addition to the fatigue condition measures of exertion, strategic changes and performance outcomes.

Importantly, prior processing and activity (i.e. exertion) is the sole cause of the feeling of tiredness normally associated with fatigue. However, fatigue may be influenced by normal sleep cycle events (absence of sufficient rest) in terms of exertion to stay awake. Other factors may also cause exertion and the feeling of fatigue, such as having to work when feeling unwell. The contribution to the feeling of fatigue from exertion (prior processing/activity) is dynamic i.e. awareness of tiredness increases with fatigue, but as people become very fatigued awareness peaks or reduces. Circadian and homeostatic sleep drives will also contribute dynamically to the feeling of fatigue.

Note that both insufficient physiological capacity and/or affective, cognitive and conative tiredness can lead to changes in performance strategies. In other words, simple awareness of tiredness in and of itself may lead to a change in the original level of processing using normal resources. We regard this as important in accounting for the role of goal-directed behaviour in fatigue effects on performance. While lack of cognitive or physical resources may directly prevent mental processing or physical activity, we know that people rarely reach their energetic limits before they withdraw. The awareness of fatigue is primarily what makes them stop.

4.7 Dualistic accounts of fatigue

In addition to experiential, physiological and performance definitions of fatigue, fatigue has also been characterized along other dimensions (Table 2). While each in its own right may be considered too narrow in focus for describing and tackling the problem of fatigue in human transport operators, each may add to our understanding of the concept.

Table 2. Various dualistic accounts of fatigue.

Category	Example	Source
Primary/secondary	Largely in medical use to dimensionalize Chronic Fatigue Syndrome, where primary fatigue refers to the core physiological fatigue process i.e. loss of efficiency in nervous system, and secondary fatigue describes related effects of fatigue e.g. depression, sleep disturbance.	(Jason et al., 2004)
Acute/chronic Normal / pathological	Little consensus on time-point at which fatigue becomes chronic, from 6 weeks to 6 months. Some clinicians equate this dimension to normal / pathological fatigue. Acute fatigue occurs in healthy individuals, where it is a normal protective function with rapid onset, short duration, and often a single cause. Chronic fatigue affects general life quality, is often associated with other illness, persists and is "multifactorial in etiology".	(Christodoulou, 2012; Shen et al., 2006; Strober & Deluca, 2013)
Local / general	"one can conceive of different kinds of fatigue, such as local physical fatigue (e.g. in a skeletal muscle), general physical fatigue, mental fatigue (e.g. following sustained attention due to a long-lasting high mental workload) or "central nervous system" fatigue (sleepiness).	(Lützhöft et al., 2007)
Active/passive	Active fatigue occurs during prolonged continuous perceptual-motor task performance, in contrast to passive fatigue, which requires system monitoring with either rare or even no overt perceptual-motor response requirements. The latter is closely linked to vigilance and increasingly implicated as vehicles become more automated.	(Desmond & Hancock, 2001; Saxby et al., 2013)
Central/peripheral	Central fatigue describes a failure to initiate or sustain attention tasks and physical activities requiring self-motivation. Involves central nervous system. Peripheral fatigue arises from muscle failure in neuromuscular transmission, and results in reduced force or power.	(Chaudhuri & Behan, 2000; Jason et al., 2005)
Psychological/ physiological	Psychological fatigue is a state of weariness related to reduced motivation and associated with negative affect conditions like stress, depression or anxiety. Physiological fatigue is loss of force-generating capacity in muscle or organ.	(Shen et al., 2006)

4.8 Summary

Thus fatigue is a complex and dynamic phenomenon, and varying dimensions will need to be accounted for in studying fatigue in human transport operators.

In defining fatigue, a triad of physiological, performance and perceptual aspects is increasingly accepted. Neither one aspect can be determined by the other two, and each is thus required in order to fully understand and tackle fatigue. Reflecting this trend, Miller (2012) claims that researchers are moving towards a systems perspective of the impact of multiple components of fatigue on the operator interactions with technology. The implication is that any study of fatigue would do well to measure the three main dimensions of fatigue. Whether and how this can be done in practice is the subject of Section 6, after we have considered some ways in which models inform about how we can think about fatigue.

5 How should we think about fatigue?

We have argued that fatigue is best construed as multidimensional, with experiential, physiological and performance aspects. Accepting this, models should explain how the different aspects of fatigue are related to each other in addition to being able to account the many findings on fatigue. Models should also help us understand the causes and effects of fatigue, and how fatigue interacts with other energetic constructs.

One of the most successful models relating to fatigue is the so-called two-process model of sleepiness. Beginning our discussion with this model is useful in that it will help clear up confusion caused by mixed use of the terms “fatigue” and “sleepiness”. By outlining what sleepiness models do and do not tell us about fatigue, we will be able to consider whether models of fatigue can add anything useful to models of sleepiness. We will find that in order to be useful, conceptual models of fatigue need to add to models of sleepiness by explaining how sustained activity (exertion) results in a change in the quality of performance, and furthermore how the nature of that change varies according to the type of activity performed.

Finally, discussing how sleepiness is modelled will help us understand the findings that have been made to date on the neuroscience of fatigue, which in large part equates to the brain physiology of sleep loss. There is much still to learn about the physiology of both sleepiness and fatigue, despite a lot of recent progress. Conceptual models are therefore still required to structure the data and enable us to make predictions about the causes and effects of fatigue in different situations.

In this section we present a selection of such models, which we think are highly relevant to the safe conduct of human transport operators.

5.1 Models of sleepiness

According to widely accepted models, sleepiness in otherwise healthy people is strongly regulated by two main factors, commonly referred to as homeostatic and circadian factors (Borbély, 1982). The homeostatic factor gives increasing sleepiness with time spent awake, and to a lesser extent activity while awake. After we have fallen asleep, this factor is slowly reduced, so that on waking alertness is restored and the cycle begins again. In more recent models a factor controlling wakefulness is added to the homeostatic factor profile, such that sleepiness is determined by the balance of sleep/wake factors, but the overall effect on sleepiness remains essentially unchanged (Johns, 2000).

Despite increasing homeostatic pressure to sleep, we can feel just as awake in the afternoon as in the morning. This is because sleepiness is also influenced by the circadian part of the process, which is driven partly by an internal clock and partly by external factors such as light. Under normal conditions, the circadian part of the sleepiness regulation process drives us towards peak alertness towards late afternoon (via a post-lunch dip), and peak sleepiness in the early hours of the morning. The total effect of the homeostatic and circadian processes together is that we are alert throughout most of the morning, afternoon and early evening, but that alertness decreases quite rapidly as the night progresses, i.e. as both homeostatic and circadian processes drive us towards sleep.

The sleep homeostatic process in normal healthy people is influenced by and can be approximated by sleep history, as described by the hours of wake since last sleep, hours of last sleep and sleep debt from previous days. The latter is described by the duration, continuity and content of recent sleep episodes (Åkerstedt et al., 2007). Circadian influences will be determined and can be measured by time of day.

Almost all accepted models of sleep propensity can be related in some way to the above description. Some authors have called for models of sleepiness to better account for trait (longer term, person-specific sleepiness) and state (shorter term, situational influences) determinants of sleepiness. One way in which this has been done is to categorise sleep and wake drive components as either primary (controlled by central nervous system) or secondary (controlled by homeostatic or environmental properties e.g. light) (Shen et al., 2006). Another attempt has been to explain the phenomenon of "owls"and "larks" as due to the particular phase timing of the circadian rhythm in different individuals (Kerkhof & van Dongen, 1996). Nevertheless, the main influences on sleepiness remain homeostatic and circadian processes.

Models of sleepiness are gaining support and detail from neurophysiological findings

Models of circadian rhythm are being supported by growing research into neuroscience models. A unitary circadian pacemaker has been located in the suprachasmatic nuclei of the hypothalamus of the brain that communicates with differentiated satellite pacemakers distributed throughout the rest of the brain and body (Banks et al., 2012). Various photoreceptors and visual pathways involved in relaying the influence of (primarily blue) light to the suprachasmatic nuclei are also being elucidated, as are output pathways such as the pineal gland (Golombek & Rosenstein, 2010). Knowledge is coming together on how these neural pathways are involved in mechanisms explaining how light and the "sleep hormone" melatonin advance or retreat circadian rhythms.

The neurobiology of the sleep homeostatic process is less well known. It is known that as the brain uses cellular energy in the form of adenosine triphosphate, or ATP, the metabolic by-product adenosine is produced, which then signals sleepiness by binding to the adenosine receptor of the brain neurons (Banks et al., 2012). Caffeine acts as a stimulant by binding to the adenosine receptor and blocking the action of adenosine. However, we do not know what happens during sleep to restore wakefulness, and adenosine is probably part of a "complicated cascade of compounds and interactions" involved in the sleep homeostasis, most of which we do not understand (Banks et al., 2012).

Various wake-promoting centres in the brain are involved in alertness maintenance. These utilise various neurotransmitters (e.g. serotonin, dopamine, histamine, adrenaline) to activate neurons. The ventrolateral preoptic nucleus may monitor the sleep propensity of the brain, switching the whole brain over into sleep mode when propensity reaches a certain level (possibly related to extracellular ATP levels), by blocking the action of the wake-promoting centres by producing the inhibitory neurotransmitter GABA (Fuller et al., 2006). The ventrolateral preoptic nucleus tends to get stuck in either "on" or "off" mode, thus helping to prevent waking after we have fallen asleep, i.e. sleepiness must be dissipated completely before it will stop its inhibition of wake-promoting centres.

Importantly, the thresholds for homeostatic sleep pressure that trigger ventrolateral preoptic nucleus state switches are thought to vary according to the circadian rhythm. This explains why it is easier to sleep at night than in the day, given the same level of homeostatic sleep pressure.

Finally, there is also some understanding of how deliberate effort can produce a different neurotransmitter (orexin) that stimulates arousal centres, and that this may help resist ventrolateral preoptic nucleus-induced switching into whole-brain sleep. This gives a physiological basis to observations that humans can sleep-deprive themselves, at least to a certain extent.

Thus models of sleepiness are fully supported by the neurophysiological findings. Late in the evening, circadian pressure for wakefulness falls, along with systematic changes in body temperature and melotonin secretion; the homeostatic pressure for sleep also continues to increase. The ventrolateral preoptic nucleus switches to wake inhibition mode, and we sleep. While we sleep, sleep homeostatic pressure dissipated, but circadian pressure for wake declines further, bottoming out in mid sleep. In the morning it increases again and this, together with dissipated homeostatic pressure switches the ventrolateral preoptic switch back into the "on" position.

Despite increasing knowledge of the neurology of the sleep-wake cycle, there is much work to do to understand the variability in cognitive performance that is characteristic of sleep loss. Neuroimaging has revealed reduced metabolic activity in the thalamus following sleep deprivation, which indicates that sleep deprivation affects the brain's arousal systems, and thus could explain lapses in attention, cognitive variability etc. (Wu et al., 2006). Microsleeps have also been imaged as attenuations in processing due to reductions in activity in frontal and parietal control (cognitive control) and thalamic (arousal) areas. The cognitive effects of sleep deprivation are further discussed in Section 6.

Models of sleepiness can explain fatigue problems in shift workers

The two-process model of sleepiness has been extremely useful in explaining the problems faced by shift workers, whose timing of sleep and wakefulness is often out of synch with the circadian rhythm. Night workers who must sleep in the day often sleep poorly, because the circadian drive for wakefulness is high. This poor sleep amplifies the homeostatic drive for sleep, which is then further amplified by the fall in the circadian drive for wakefulness as they begin work at night. Attempts to adapt to night shift are only successful to a limited extent. This is because circadian influences are determined not only by environmental triggers such as light or social interaction, which slowly adapt to altered sleep time, but also in part by an internal clock, which does not adapt (Folkard, 2002). A major change in the time of day of sleep thus results in mismatch between homeostatic and circadian profiles, poor coordination of the sleep/wake drive and associated physiological processes, and ultimately poor sleep.

Models of sleepiness can help understand the causes of sleepiness in human transport operators

The two-process model can help understand the causes of sleepiness in human transport operators. These have been summarized, for instance, as (Åkersted, 2000):

1. the time of day of the transport operation (e.g. night/early morning)
2. a long duration of wakefulness
3. inadequate sleep
4. pathological sleepiness (sleep apnea, etc.)
5. and prolonged work hours (not necessarily operating the vehicle).

Limitations of sleepiness models

Current sleepiness models do not explain everything about sleepiness. Although recent models have addressed the problem of sleep inertia by adding a third process to account for time between waking and alertness (Åkerstedt et al., 2004), there is still lack of accounting for the moment to moment variation in homeostatic drive (Banks et al., 2012). There are also claims that consistency of sleep, and not just the amount or quality of compensatory sleep, is important to account for recovery from acute bouts of sleep loss (Barber et al., 2010). And as we have already noted, contemporary models do not account for trait influences on sleepiness (Cluydts et al., 2002).

A further limitation of these models is that they do not explain what happens to performance. To develop and validate the models, self-reports are collected using rating scales that assess either current sleepiness (e.g. (Vakulin et al., 2011)) or sleepiness across different situations (Johns, 1991). Alternatively sleepiness is observed by measuring of physical signs of sleepiness such as blink rates, time taken to fall asleep under controlled conditions (e.g. multiple sleep latency test), or electrophysiological measurements (Curcio et al., 2001). The ultimate outcome of interest is thus not performance, but sleepiness. While this has important implications for safety, there is lack of agreement about correlations between both subjective and objective measures of sleepiness, and measures of sleepiness and performance.

5.2 Does fatigue add anything useful to sleepiness?

Many studies have been published on the effects of extreme tiredness in human operators, and many of these operationalise tiredness by restricting it to sleepiness. This is understandable given recent progress in the physiology of sleepiness and because the implications for safety performance of operators falling asleep are so serious. So what then is the point of modelling and studying fatigue?

Sleepiness may share many of the same symptoms as fatigue, and because it is easier to operationalise, has often be diagnosed in favour of fatigue by clinicians (Shen et al., 2006). Fatigue is viewed by clinicians as being mentally or physically worn out generally, but not necessarily sleepy. Two studies show that at least half of patients with sleep disorders have exclusively fatigue, whereas only about 5 per cent were sleepy (general daytime sleepiness) without being fatigued (Dement et al., 2003). About 20 per cent of the patients were both fatigued and sleepy. These studies suggests two things: that fatigue and sleepiness are two separate dimensions, and that fatigue is more common than sleepiness, at least in patient samples. If this also applies to tiredness in normal people, then accounting for fatigue would add explanatory power to sleepiness in terms of how tiredness affects performance in human transport operators.

Many sleep researchers seem to play down the need to account for mental fatigue when explaining why we become sleepy. Sleep homeostasis and circadian rhythms are often seen as all important (Dawson & McCulloch, 2005). This is also apparent from lack of formal descriptions of the role of sustained activity in contributing to homeostatic pressure in the original two- or three-process models. The assumption seems to be that doing work increases sleep homeostatic drive, but this is less than satisfactory given how fatigue can lead either to exhaustion and sleepiness, or inability to sleep (Maslach, 2000). Sleepiness may also be influenced by other aspects of the job than mere task performance. There is a need to consider the overall operation in which the human transport operator is involved and influences on sleepiness such as monotony, physical exertion, psychosocial demands, in addition to more directly relevant aspects such as shift pattern or hours of work.

In addition to helping to explain the occurrence of sleepiness in transport operators, fatigue, as we have defined it, could help understand how *performance* is influenced by both sleep drives and work under different operational conditions. The wakeful, highly fatigued operator may also be dangerous in terms of the slow response times or lack of attention he or she may exhibit, but sleepiness models do not account for this. Models of fatigue may give a mode comprehensive account for how sleep drives and work (exertion) of the human transport operator affect performance in the short and longer term.

Other reasons for considering the wider concept of fatigue in studying safety effects on human transport operators are as follows.

- Laboratory or simulator studies on vigilance tasks do show a rapid decline in performance over time, the classic vigilance decrement (Smit et al., 2004; Thiffault & Bergeron, 2003). This is of concern because vigilance is a central task of the human transport operator.
- While experiments show sleep drive does influence performance of sustained mental tasks, the length of time certain tasks are performed also has main effects in itself (van Dongen et al., 2010).
- Many empirical studies include time on task as a contributor to fatigue over and above sleepiness and/or because monotony associated with driving long distances may unmask sleepiness (Connor, 2011).
- There is good evidence for a circadian rhythm in the risk of traffic accidents and industrial injuries but in both cases the peak occurs earlier than would be expected if it was solely mediated by variations in sleepiness, i.e. at midnight rather than early hours between 3 am and 6 am. According to Williamson et al. (2011): “the most obvious reason for this discrepancy would appear to be that the trends in risk are confounded by differences in other factors that contribute to overall fatigue”.

In summary, one of the problems of operationalising tiredness by restricting it to sleepiness is that it is possible for a person to be extremely tired without being sleepy, to such an extent that performance is affected. In the short term this may be caused by sustained performance in response to demands that are perceived as important. In the longer term this may be due to burnout (Maslach, 2000), which is associated with fragmented, poor quality sleep. Similarly, mental load (extreme underload or overload) may well cause performance decrements, whether it leads to problems over the course of hours, or whether task-related tiredness builds up over days. If the tasks of the transport operator lead to tiredness-related safety performance decrements, fatigue may help.

Below we summarise the reasons to study the experiential, physiological and performance aspects of fatigue in relation to human transport operator performance, and not just sleepiness:

- Problems related to fatigue may be more common than those related to sleepiness.
- Fatigue as we have defined it may help explain and predict variation in individual human transport operator performance.
- Some mental tasks, especially those involving vigilance, when performed for a sustained period lead to performance decrements independent of sleepiness.
- Lack of exact correlation between circadian lows and accidents indicates that the effects of fatigue are involved in safety performance.
- Fatigue may help account for the longer term effects of workload or demands on performance.

5.3 The physiology of fatigue

The most obvious form of physiological fatigue is muscular, and related to insufficient oxygenation consequent depletion of glucose supply at cellular level, as well as lactate accumulation. Some authors claim that similar mechanisms involving brain glucose levels are the basis of mental fatigue, thus providing the basis of a mechanism for general fatigue (Matthews et al., 2012). Common mechanisms are also proposed for the interactive effects on performance of sleep deficit and doing work, in which sleep loss results in insufficient repletion of brain energy (glycogen), leading to a lack of back-up energy for work (Bennington & Heller, 1995; cited in Hockey, 2012).

However, accounts of resource depletion as limiting for task performance (Helton & Warm, 2008; Smit et al., 2004) are opposed by accounts of psychological constructs as limiting e.g. lack of arousal, boredom, mindlessness or underload being limiting (Pattyn et al., 2008). Indeed, some authors doubt the extent to which physiological energy supplies could ever by directly limiting for performance, even of muscular activity (Noakes, 2012). The argument of the Noakes' so-called Central Governor Model is that the heart itself is a muscle that the body cannot allow to become depleted of energy. Therefore, some subconscious governing process in the brain must monitor and forecast physiological states and energy use, such that systems are shut-down before energy supplies become limiting (Ullevoldsæter & Frøyd, 2013). In this way catastrophe is avoided. Here fatigue is not only related to the work that was done but that work remaining to be done. Similar arguments are made in the case of mental activity, as described later (Hockey, 2012).

The Central Governor Model is not inconsistent with an earlier physiological model of fatigue, which describes that perceived fatigue states vary according to antagonistic activating and inhibitory mechanisms in the nervous system (Grandjean, 1970). If the inhibitory system dominates, then fatigue results, where alertness is conveyed by the activating system. Thus fatigue is a state of decreased alertness. This model is related to traditional arousal theory, that performance variation across tasks reflects cortical arousal (Åhsberg, 1998).

In the last few decades brain imaging and other tools and techniques have become available with which to study actual neural processes in people who are fatigued. These show that several brain arousal systems are involved in fatigue. Evidence is increasing that sleep is not related to whole-brain energy levels, but rather is related to neuronal assemblies. Importantly, some of the assemblies involved are thought to be the cortical columns related different aspects of information processing in the brain (Koch, 2004). It is possible for some of these to be in a "sleep-like" state while adjacent columns are awake (Rector et al., 2005). Importantly, this is more likely if the cortical column has been used more intensively. Cortical columns in sleep-like states do not process information accurately, which may contribute to failure of a cognitive faculty (Banks et al., 2012). Thus it has been proposed that the *neurological* basis of fatigue may resemble that of sleepiness, i.e. switching off of local neuronal assemblies can occur both after continual normal use throughout the day (sleep homeostasis mechanism) or intensive use during sustained tasks (fatigue) (van Dongen et al., 2010). One theory is that the ventrolateral preoptic nucleus (see above) maintains an overview such that a person is not awake when an excess of neuronal assemblies are in a sleep-like state, but during self- or other-imposed sleep deprivation, uncoordinated brain conditions may exist.

Finally, some progress has been made to relate chronic fatigue to distinct biochemical pathways, where the metabolites of cellular energy production and the stress hormones produced by the hypothalamus, and adrenal and pituitary glands are implicated (Watanabe et al., 2012).

5.4 Conceptual models of fatigue

From even the most up to date accounts of the neurology of fatigue, it seems instinctive that performance would be expected to decrease with time on task. However, many studies fail to show a linear relationship between driving and time on task (Hancock et al., 2012). Likewise, it is hard to see the effects of sleep loss on performance in highly motivated military crew who are fatigued (Johnson and Naitoh, 1974). There are several explanations for this.

- A picture has emerged that a combination of total time spent at work (not necessarily on task) and time of day at which work occurs is important in terms of performance effects. Circadian lows can suddenly reveal the effects of fatigue that the individual is able to counter at other times of day, and that emergencies can also expose the effects of fatigue (Williamson et al., 2011). While fatigued crews may be able to cope with routine by strategic adjustments or increasing effort, they are more exposed in emergency situations.
- In accounting for time on task effects, we must also consider people's resilience to fatigue and their ability to adapt. Individuals have coping strategies, e.g. increasing distance to car in front, lowering risk thresholds, increasing mental effort. At a higher level, truck drivers cope by moving to better run companies, and those who cannot cope with fatigue change occupation.
- Different performance functions may be differentially susceptible to the effects of fatigue. For instance, in a study severely limiting sleep duration over weeks (to per night), it was found that auditory vigilance and logical reasoning were not affected, even though ability to ignore distracting information was (Gawron, 2000).

Thus the physiology of fatigue, much of which is derived from animal experiments, is nowhere near being able to explain the somewhat complicated performance effects of fatigue in humans (Banks et al., 2012). Moreover motivational and strategic aspects of the fatigue process do not appear to map onto individual processing components of the brain (Matthews et al., 2012). A related challenge for physiological models is explaining how energetic constructs such as workload or stress contribute to fatigue effects on performance of human transport operator. In short, there is still a need for conceptual models to help understand and study fatigue.

Below we consider two main conceptual models that consider how people maintain performance in the face of fatigue. Discussion of those models us assisted by a brief consideration of fatigue in relation to other energetic states associated with working.

5.4.1 Distinguishing fatigue from stress

Despite attempts to highlight the differences, there still remain difficulties in distinguishing fatigue and stress. This is partly because people have difficulty distinguishing between the two states, and partly because researchers disagree about the extent to which the concepts overlap. Some authors have claimed that fatigue is a form of psychological distress, and that the term really adds nothing beyond the notion of stress. According to (Tepas & Price, 2000), "Stress and fatigue refer to multidimensional and interacting constructs. Those who use stress and fatigue as references often fail to recognize this complexity and use these words in confusing ways". Another complication is that chronic fatigue is often conceptualised as a symptom of chronic stress. Such complexities cause Kaillard (2000) to claim that it is better to think of "energetics" than terms like fatigue and arousal, which have too many unwanted or confusing connotations.

However, studies measuring the two concepts find substantial mutual exclusion between fatigue and stress. Fatigue and psychological distress were measured among 12000 employees in the Masstricht Cohort study using respectively the Checklist Individual Strength, and the General Health Questionnaire (Bültmann et al., 2002). The prevalence of fatigue and stress was 22 and 23 per cent, respectively, but 47% of those reporting fatigue reported no psychological distress. Other studies also find partial correlations of around .5 for the two conditions (Bültmann et al., 2002).

A consideration of fatigue in the context of Lazarus and Folkman (1984)'s transactional model of stress helps explain the reasons for the close association and differences between fatigue and stress. According to the transactional model, stress is a process that results when demands (stressors) in the environment are appraised cognitively by the individual as exceeding available resources i.e. stress is the result of a transaction between a person and his or her environment. If fatigue is perceived as threat to performance through increasing depletion of resources due to sustained activity, then it may result in stress as soon as a person believes that his or her resources or ability to cope are insufficient to meet perceived demands (Figure 1). Attempts to adapt by increasing effort in order to meet demands may only hasten the pace of fatigue.

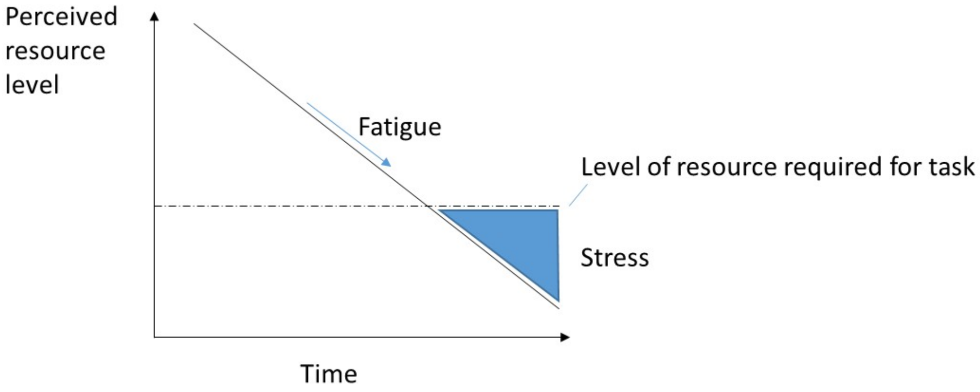

Figure 1. Illustration of relationship between fatigue and stress.

The close links between fatigue and stress have led to several attempts to conceptualise the effects of fatigue on performance using theories of stress. This *could* be conceived as the basis of the first model we consider below, the contextual control mode (CCM), but this is somewhat controversial, as will be explained. A second approach to explaining the effects of fatigue on performance is the Dynamic Model of Stress and Attention. This is less controversially based on a theory of resource depletion, and is also considered below (Hancock et al., 2012). The transactional model of stress has also been adapted specifically to explain how fatigue affects driving performance (Matthews, 2002). Like the CCM, the appraisal by the person is all important in interpreting the effects on performance. We do not consider the adapted transactional model of stress further in this report.

5.4.2 Fatigue as an indicator allowing for adaptation to work by changing resources and strategies

As we have discussed, the idea that the experience of fatigue is linked to perceived resource depletion is not uncontroversial. Researchers noticed a long time ago that a fatigued person is one who is not necessarily unable to work, but is more likely to have a lack of desire to work (Bartley & Chute, 1947). This reflects on the volitional aspect of the feeling of fatigue, that there is a need to withdraw even though it is possible to carry on. Such observations have led to the conceptualization of fatigue as an adaptive mechanism by which we choose what to do rather than do too much (Hockey, 2012). Some go as far as to claim lack of connection between work and fatigue, i.e. if we feel we are in control or there is flow, work is not fatiguing (Csikszentmihalyi, 1997). Thus the feeling of *fatigue may be a signal that our behaviour is not aligned with our goals or desires*, a signal that we should withdraw or choose to do something else.

Hockey (2012) supports this view by questioning assumptions that sustained mental activity leads to performance decrements due to depletion of some limited energy supply. Whereas Hancock et al. (2012) call for a unitary approach to mental and physical fatigue based on common cause of glucose depletion, Hockey (2012) contends that nothing in the literature that suggests a depletion of energy related to use of local brain functions. Furthermore he points to the selfish brain model (Peters et al., 2004), which holds that it is not possible for the brain to be deprived of energy, as it is always served first. Hockey (2012) also points to lack of accounts explaining how fatigue is restored as energy is restored.

There are two ways to account for Hockey's view in explaining connections between fatigue and stress. The first is that Hockey's idea of mental fatigue resembles that of Noakes' on physical fatigue discussed earlier, where task withdrawal in real world activities is not due directly to failing resources, but to a self-limiting and very conservative cognitive and emotional process (i.e. fatigue) related to a subconscious preservation mechanism derived from the discrepancy between current rate of energy use and projected long term time-energy profile (Noakes, 2012). This view may be consistent with our presentation of fatigue as an indicator that is *perceived* to be linked to physiological resource depletion, and which therefore leads to stress.

However, Hockey contends that rather than protecting performance from resource depletion, fatigue is a mechanism whereby performance is protected from interference from lower order desires or drives, which may become increasingly salient and place demands on attention the longer they remain unmet (Hockey, 2012). A closely related explanation is that the operator may be driven to preserve extrinsic goals at the expense of intrinsic ones. Such a view may be accommodated in our conceptualization of fatigue and stress as illustrated in Figure 2. Thus the longer work goes on the greater the misalignment between behaviour and desires or lower-order goals, and the more fatiguing work is. However, in this case it is less clear how and when stress is related to fatigue. One possibility is that stress grows continuously in line with the time spent carrying out misaligned activities, but then we must questions whether stress actually differs from fatigue at all. As we have seen, this view is not supported by the clinical data.

A preferred explanation therefore is that stress occurs once a threshold of misalignment is reached, which could be measured in terms of perceived demands of the misaligned task and time spent on the misaligned task. This idea is the one illustrated in Figure 2.

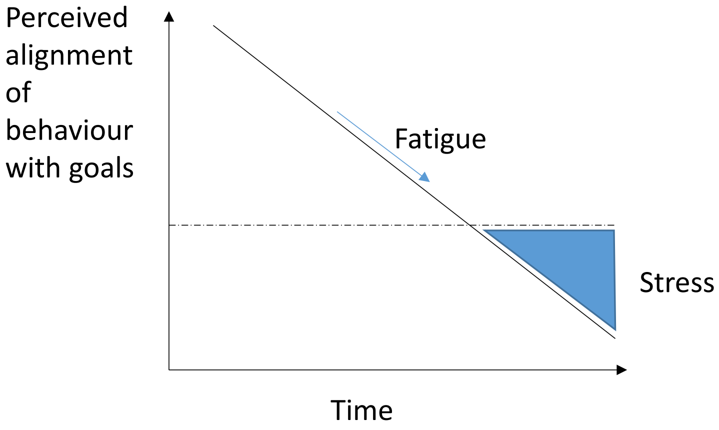

Figure 2. Alternative illustration of relationship between fatigue and stress.

The view that fatigue is due to misaligned activities must be reconciled with the fact that it is possible to feel fatigue after being intensively involved in doing what one enjoys, i.e. motivation cannot explain everything. The possibility remains, however, that the homeostatic sleep drive and other lower order drives might account for why we may become tired after performing activities for which we are intrinsically motivated. If this is the case then fatigue, while supplementing sleep drives in helping to explain performance effects, may not necessarily be related to resource depletion.

Whatever the case, the main tenet of adaptive accounts of the effect of fatigue on performance is that humans rarely reach their energetic limits at work. Motivation and increasing stress thus account for a substantial part of the widely varying effects of fatigue on performance, whether the cause of that fatigue is projected resource depletion, mismatch of goals and behaviour, or both.

5.4.3 Compensatory control model (CCM)

This model of self-regulatory control is the most well-known accounts of fatigue as an adaptive mechanism for the preservation of performance. (Hockey, 1997). In line with earlier theories, the CCM assumes that regulation of action involves cost-benefit decisions about the use of effort and the relative value of different goals. The CCM describes two levels or feedback loops of compensatory control. One is associated with lower level, routine regulation and the other with upper level, effort-based regulation, where effort is subjective awareness of resource deployment. Increasing control demands in the lower level loop are detected by an "effort monitor" in the upper level loop, thus explaining observations of reports of subjective effort to task-induced increases in demand. Perception of increased demands causes control to be shifted to the higher level temporarily, where several modes of regulation can be selected.

An important aspect of the CCM is that the effort monitor has lower and upper set points, which can be adjusted in response to demands. The lower level is default for a given task environment. Increase in demands below this level are not perceived as effortful, and control of performance appears automatic (lower level control). The upper set point is an operational maximum, and the difference between the two set points is the "reserve effort budget" for meeting additional demands.

The lower level set point is thought to be quite stable for an individual, but the upper set point is more motivational in origin and more variable. Thus the upper set point may be increased (effort budget increased) in the face of high demands, in order to achieve valued outcomes. On the other hand it may be decreased when the person is fatigued, ill or chronically stressed. A small reserve budget is associated with overt decrements in performance under stress, while a larger budget is more likely to be associated with sustained performance.

Importantly, however, whenever compensatory control induces effort, especially in response to continued high demand, self-regulatory activity has emotional and physiological costs to the person. These costs are linked to increased dominance of the sympathetic nervous system and adrenal activation (Kahneman, 1973), and will be experienced by the individual as strain.

It is important to note that stress is seen as the result of mismatch between actual and desired task states, but effort-based compensatory control will also be needed for preventing loss of task goals under circumstances other than stress, including external or internal distractions and increased processing demands.

The model describes that effort is maintained in order to conserve primary task goals, in spite of the fact that it is "subjectively aversive", because sensitive task goals are protected by focal attention. It accounts for systematic findings that primary task performance is maintained under stress or fatigue, and that such performance maintenance is typically accompanied by high levels of physiological activation and subjective strain.

The CCM describes different modes of coping.

The level of **active coping** depends on levels of demands and effort. Where the latter are moderate, the lower set point of the effort budget is adjusted upward to meet demand, but effort remains well within reserve limits. There are physiological (elevated catecholamine but no increase in cortisol) and cognitive (increased working memory or executive control) implications.

Where demands are high and the individual is required to operate at higher levels of effort for a period of time, there are two options. The first is to increase the upper set limit of the effort monitor, and accept associated energetic costs (effort with distress). Here there will be anxiety, fatigue, and high levels of sympathetic dominance with increased catecholamine and increased cortisol. While aversive, this mode of response may not pose serious problems if short and temporary.

A second alternative in the face of high demands is the **passive coping** mode, where performance targets are adjusted downwards (e.g. reducing required accuracy or speed or attention paid to subsidiary activities) at no extra cost to the individual. There can be "distress without effort" where the loss of performance standards is personally distressing.

How the CCM accounts for fatigue

The CCM accounts for fatigue in several ways (Hockey, 2010).

1. Fatigue is conceptualized as the sensation that is described by the CCM as awareness of the effort monitor. Effort-based compensatory control in response to fatigue can occur not only because of increased processing demands, but due to increase salience of internal sensations. In either case, triggering of the effort monitor can be sensed as fatigue, i.e. fatigue may act to raise awareness of the need to make decisions or allocate resources to cope (Hockey, 2012). In this way fatigue acts as a marker of cognitive conflict or discomfort, whose purpose is to cope by influencing a change in goal direction by promoting increase bias against current activities. Conceptualising fatigue in this way, the CCM predicts that performance will be affected in various ways, depending on compensatory strategy. On sensing fatigue (triggering of the effort monitor), cognitive awareness may cause the sporadic interruptions in the flow of performance involved in continuous response tasks. Then, the person may decide to increase effort budget in order to maintain the current goal where that goal is perceived as important. Although there will be no immediate detectable change in performance, an increase in effort will be associated with strain and have latent decrements in performance. Alternatively the person may choose to maintain the effort budget by switching goals, which will decrease performance towards the original goal, or by maintaining the same goal but accepting decrease in performance. These outcomes are consistent with evidence from early flight simulator studies, where there were three performance types over the session: no difference in performance; reduction in goals and thus effort; and increased effort with visible increases in arousal (Hockey, 2010).
2. The CCM also conceptualizes fatigue as the result of compensatory process. In other words fatigue is hypothesized to indicate the integrated regulatory effort over the period of the task i.e. the extent to which the active control mode has been adopted, the extent to which there has been active processing of

information in order to make decisions (Ackerman, 2011). Given that the perceived task demands and the associated resources required are variable (dotted line in Figure 1), Figure 1 also serves to explain how fatigue can be both a cause and result of adaptive coping. In tasks demanding a lot of resource, the line (and stress levels) will be high and processing demands involved in coping will be the main cause of fatigue. Where the resource demands and the line is low, task performance will be a greater cause of fatigue, and stress may only contribute to fatigue downstream if the task is performed for excessive periods. Here we can see the importance of considering task demands in terms of processing and time when accounting for fatigue. It also helps us understand why fatigue is also conceptualized as a response to chronic stress.

3. Although fatigue is associated more with active coping than passive, there may be higher baseline level of fatigue for those with a passive coping style, reflecting cumulative effects of unprocessed demands over successive days.
4. Fatigue due to illness or chronic conditions may also reflect a baseline reduction in adaptive capacity, and may be associated with less effortful modes of response.

Recently progress has been made towards mapping the neuroanatomical bases for the processes outlined by the CCM, but there is still much to do (Hockey, 2012), and the dynamics of adaptation are still poorly understood. Furthermore we do not know whether people select irrelevant goals because they are internally distracting (e.g. look at a mobile text message while driving) or in order to get them out of the way so they don’t interfere with the overall task (e.g. driving) (Duijts et al., 2007).

Implications of CCM for studying the effects of fatigue on human transport operators

The CCM holds that the momentary subjective experience of fatigue at work may index the need to adapt, but that longer-term physiological fatigue levels and performance decrements will be the result of the mode of coping. We should add that subjectively experienced task-related fatigue undoubtedly depends on other factors in addition to the tasks or activities one is involved with. For instance, Ackerman (2011) gives an account for dynamics of subjective fatigue in relation to cognitive performance, where subjective fatigue comprises transient affect (mood, concern, evaluation apprehension), baseline affect (type A, Neuroticism / Anxiety, Extroversion, Chronic Fatigue, negative affect), in addition conative factors (task interest, motivation, performance and effort utility).

Due to compensatory trade-offs between cognitive goals and effort, there will often be no detectable short-term change in effectiveness of task performance in the face of fatigue. However the costs of protecting performance will result in a change in system efficiency, which can be detected by subjective reports, physiological measurements, secondary tasks or long-term performance.

Importantly system efficiency may be a measure of how well the system can absorb future demands, which may have important implications in terms of accident prevention in emergency situations.

In some cases fatigue caused by chronic stress or illness may eventually result in reduction of maximum effort budget and primary performance decrements, or attention may be withdrawn from the central task to deal with perceived threats to emotional stability (Cameron, 1973).

5.4.4 Dynamic Model of Stress and Attention

Unlike the CCM, the Dynamic Model of Stress and Attention is based on the premise that fatigue is related to perceived resource levels, and can therefore lead to stress (Hancock & Warm, 1989) (Figure 1). In addition it attempts to account for the dynamic interactions between input factors (task characteristics), process factors (fatigue/stress) and output factors (performance decrements) that occur in real life. For example, on observing performance decrement, people may become more stressed or change tasks, and task characteristics will have effects on performance both as a result of the nature of those tasks (e.g. demanding versus simple task) and as a result of transactional processes between the task nature and motivations of the person (e.g. person who likes demanding tasks vs. one who doesn't). Consistent with this are observations that the nature of the task has generic effects of fatigue levels that should be accounted for (Ackerman, 2011; Ackerman et al., 2012).

The model describes that stress (in this case either from mental underload or overload) will increase until a psychological zone of maximal adaptability is reached. Beyond this threshold lies the physiological zone of maximal adaptability, and beyond this injury is implied. As it is reached first, the psychological zone is protective, affording the individual an emergency buffer of extra energy, and thus the model is consistent with Noakes' account of muscular fatigue described earlier. The problem is that the human is resilient, and can get used to using the buffer of energy, but if he or she does so chronic stress can result. In evolutionary terms the buffer was meant for occasional threats in which risk of injury were preferable to risk of death. The problem is that today's society is such that we are motivated to work and perform to the extreme, and the threats that we concern ourselves with (e.g. job loss) are ever-present and seemingly real, even though they are often imagined.

When considering fatigue, the model's authors describe that the individual must be motivated (intrinsically or extrinsically) to do a task in order for it to be a source of fatigue (Hancock & Warm, 1989). That is, fatigue will become an issue only if the person is driven to adapt in order to compensate to sustain performance. In this sense the model is similar to Hockey's i.e. it accounts for the role of fatigue in self-regulation of performance.

Notably the model describes that the nature of the task is important in terms of the attentional activity that the task demands. Thus in conditions of extreme mental overload or underload a person will carry out a task requiring considerable attentional activity over a sustained period. Attempts to adapt will be directed at sustaining attentional activity, but as resources are depleted, psychological adaptability will be reduced.

The model differs from Hockey's (2012) in two ways.

1. Motivated people whose tasks are in line with intrinsic goals can still become fatigued.
2. An evolutionary role for fatigue is given as a subjective state indicative of incipient failure of the steady-state supply of necessary energy in both its putative physical and cognitive forms (Hancock et al., 2012).

As we have seen, in cognitive fatigue the threat to performance is depletion of attentional resources. On the basis of recent findings in neuroscience it is suggested that attentional resources reflect levels of extracellular glucose within the active CNS. "Thus, the depletion of resources with specific forms of task demand represent a diminution of available systemic energy at specific modular sites involved in response to specific cognitive demands. Fatigue, as a general overarching subjective apperception, may involve summative assessment of overall available energy, or may be triggered as a threshold response to specific forms of depletion, contingent on the repetitive task that is being undertaken" (Hancock et al., 2012).

Effects of fatigue on performance

The Dynamic Model of Stress and Attention predicts the performance effects of fatigue by invoking the idea that attention oscillates between sampling of the environment and sampling of the self (Wickens, 1987). With a lot of stimulation from the environment and little perceived threat to the self, the greater share of sampling is directed to the environment. Conversely, with minimal stimulation and greater concern for the self, external sampling decreases. The efficiency of sampling in either condition depends on the level of attentional resources available, i.e. sampling will be poor in a fatigued condition.

When there is constantly high perceptual motor demand, as in driving on a demanding road, fatigue due to sustained demands results in depletion of attentional resources, meaning that external sources are sampled less often. This results in less frequent steering adjustments that become more erratic as weaving increases. This is active fatigue and it results from continuous activity.

Attention is also reduced by underload i.e. when there is need for continuous monitoring without intervention, e.g. long distance driving on straight roads or piloting a plane on transoceanic flights. Sampling of the environment, which is already low, is reduced further by fatigue, as is our ability to monitor the self-state i.e. we may become less aware that we are fatigued. This is "passive fatigue" resulting from vigilance.

Thus the model predicts that fatigue will impair performance more rapidly when the demands of a prolonged task are very low (underload) or very high (overload). This is supported by simulator experiments showing greater performance decrements for prolonged driving on straight roads (underload) than on curved roads (moderate load) (Desmond & Hancock, 2001); and from air traffic control simulations showing greater performance decrements under conditions of underload than of high/medium load (Desmond & Hoyes, 1996).

Task-induced fatigue effects will tend to be more detrimental when the task is attentionally demanding (Warm, 1993), implying a loss of functional resources (Matthews & Desmond, 2000). But contrary to this idea, Desmond and Matthews (1997) found that drivers can compensate behaviourally for task-induced fatigue when task demands are high (simulators). Performance appears to break down only when the task is relatively easy (straight road driving). Due possibly to failure to apply sufficient task-focused coping because (a) subjects report less coping (b) steering reversal data show active control of the task is diminished. Drivers also report reduced active coping following long journeys in actual real-world driving (Desmond, 1997). Loss of active coping may be due to beliefs that the goal of lateral tracking is less important when the road is straight, and that they can address the conflicting goal of reducing increasingly salient internal discomfort by reducing effort (Matthews & Desmond, 2000).

Implications of the Dynamic Model of Stress and Attention for safety-related functions of human transport operators

The Dynamic Model of Stress and Attention adds that environmental factors can induce fatigue in their own right (Hancock & Verwey, 1997). Tasks have been characterised for their fatiguing properties, in terms of information rate and structure. Vigilance tasks for instance have low event rates and restricted spatial structures. Hancock and Warm's (1989) model of stress and sustained attention (vigilance) holds that performance is optimal only when the combination of both information rate and the structure of information is optimal for the individual. Deviations from the optimal combination lead to decreased comfort through greater need to adapt and increased perceived task load and stress, leading to reductions in performance. In most situations the operator does not have control over this combination i.e. over the factors necessary for optimal vigilance.

Experimental studies confirm that human transport operator (driving) tasks that are monotonous and predictable are associated with performance reduction e.g. increased example reaction time or increased steering wheel movements in a driving simulator (Thiffault & Bergeron, 2003). Certainly the ability to detect critical signals over time in vigilance tasks declines in terms of accuracy and reaction time, and participants find the task increasingly demanding. However, this is undoubtedly due to both motivational aspects as well as task characteristics. Simple changes to task parameters can make an activity more or less difficult, and alter perceived workload, but they do not affect monotony. Introducing stimulus variety only delays the onset of boredom. The only way to reduce stress in vigilance optimally is therefore to allow operators to stop when they are bored (Scerbo, 2000). Vigilance is thus stressful both due to demands (task nature) and boredom (motivational aspect).

We expect generally that mental workload will increase in line with task load. This is known as association. We might for instance expect operators to experience more mental workload as traffic increases, but for air-traffic controllers controlling flight traffic this is not always the case. The reason is that effort is determined and maintained according to the individual human transport operator's motivation. Most controllers use some adaptive strategy to manage performance and their subjective perceptions of task involvement e.g. they may cease less important, peripheral tasks or increase space between the aircrafts in order to cope.

5.5 Summary

The motivation for this report is the study of how fatigue affects the performance of human transport operators. A central way in which fatigue affects performance is by causing operators to feel drowsy or even fall asleep on the job. Much progress has been made to model and predict sleepiness, and two main processes determine how sleepy a human transport operator will be. These processes can be described by the time of day and sleep history.

However, evidence shows that there are other causes of fatigue that are important for performance, and are related to exertion while carrying out the work task and other job activities over time. Thus sleepiness can be thought of as a central element of safety-related tiredness at work, whose main determinants can be considered as time of day, sleep history, and exertion. This is illustrated by Figure 3.

Although a lot of data are being generated on the neurological and physiological bases for sleepiness and fatigue, there is much work to do before we can understand how fatigue affects performance at this level. Developments in cognitive neuroscience may make it possible in the not too distant future to relate several models accounting for different effects of fatigue to distinct neural architecture. More work is needed, however, to support each of these models, and understand effects of different task and work contexts, in order to predict performance deficits. In the meantime the study of fatigue in transport operators is informed by what we perceive to be the most useful and supported conceptual approaches to the effects of fatigue on performance, represented by the CCM and Dynamic Model of Stress and Attention. These inform us that the effects of fatigue on performance depend on the form of exertion, the nature of the task and the operator's goals, skills and personality, all of which will be underpinned by a host of neuropsychological processes. It is perhaps not surprising that simple attempts to relate task fatigue to task performance reveal a complexity of results.

Both the CCM and Dynamic Model of Stress and Attention emphasise that when considering how fatigue effects performance we must attend strongly to the human transport operator's interpretation and motivation he or she brings to the task. We should consider that the human transport operator is adept at adapting to maintain performance, but that this has consequences in terms of both latent performance decrements and personal health or quality of life costs to the human transport operator. We can consider some tasks to have characteristics that can be considered inherently fatiguing in terms of performance maintenance, and this applies particularly to vigilance tasks. We should also consider task *performance* in terms of the relative contributions to fatigue from computational effort (processing of information) and compensatory effort (to maintain effort in response to operator motivation). Both of which can be caused by and lead to fatigue (Szamla, 2012). Finally, we must also attend to the dynamics of a job or task when accounting for fatigue. Thus while perceived mental workload will be an interaction between the task and the skills and interpretation of the operator, performance effort is a voluntary process under the control of the operator, who may decide to withdraw effort, increase effort or change the task e.g. deciding to make a telephone call while driving.

There are some important differences between the CCM and Dynamic Model of Stress and Attention that represent fundamental gaps in our knowledge about fatigue. Most importantly, it is not clear whether the sensation of fatigue is rooted in a sustained discrepancy between perceived required and available resources, or a discrepancy between our actual behaviour and desired behaviour in terms of intrinsic goals or drives. This must be considered alongside observed dissociation between subjective and physiological fatigue. If subjective fatigue is not explicitly linked to actual resource depletion, dissociation between subjective fatigue and performance is not surprising. A changes in strategy or increase in stress may be more directly related to experienced fatigue than changes in physiology.

Whatever the source of the experience of fatigue, it does not affect the validity of our chosen definition, which describes that the state of fatigue is due exertion, whether it causes the fatigued state due to a perceived misalignment of activities and desires or perceived lack of resources. We suspect that both may be true. Moreover the case remains that work often leads to a state of fatigue that is associated with cognitive or latent performance deficits that cannot be explained by sleep drives alone. It is the fatigued state and the associated feelings, sensations and performance affects that we wish to study. The state itself is complex, describing changes to the whole systemic organism, describing changes to the subcellular, cellular, muscular, neurology or hormonal profiles.

Heuristic for the effects of fatigue on operator performance

Neither the CCM or Dynamic Model of Stress and Attention account for sleepiness, perhaps reflecting that each model was not originally designed to account for fatigue. This is an important omission especially given that task- and sleep-related causes of fatigue interact to compound feelings of fatigue and subsequent performance decrements (May, 2011).

Below we present an attempt at a heuristic that addresses this oversight, and which draws attention to aspects that need to be considered when studying the effects of fatigue on human transport operator performance (Figure 3).

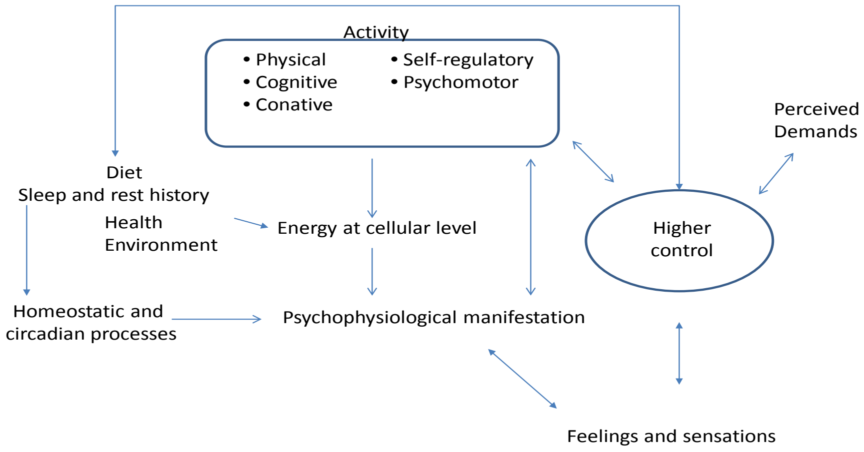

Figure 3. A holistic model of fatigue that accounts for the role of sleep. Here fatigue is not one step in the process, but is described by indices that map the system e.g. the collective state of experiential, physiological and performance/activity (physical, cognitive or psychomotor) indices.

There is no "fatigue" box in the heuristic, reflecting that fatigue is not one step or dimension but a multidimensional process, which at one point in time may be called a state. At the centre of the heuristic is the physical, cognitive or psychomotor activity that the human transport operator is performing over time, which will influence cellular energy (at least in the case of physical and psychomotor performance), and in turn the overall psychophysiological manifestation of performing over time. This manifestation may in part be determined by subconscious monitoring processes projecting future resources. Depending on the task, the psychophysiological manifestation may have direct implications for performance of activity that does not require higher order processing. This includes highly automated responses to prolonged task performance or resource depletion effects. Effects of fatigue on performance will also be determined by motivational processes that occur via the interaction of feelings and sensations and higher order cognitive processes (goal-driven activity). Thus while exertion may be due to the objective demands of a task involving psychomotor or purely cognitive functions, the level of exertion will also depend on individual variations in psychophysiology and the subjective interpretation of task demands by the individual.

The heuristic accounts for both resource limitations ("energy at cellular level") and behaviour-goal alignment (via "higher control") as sources of fatigue. Importantly it also accounts for the role of emotions in fatigue ("feelings and sensations") and the importance of subjective fatigue in influencing higher order cognitive processes. The importance of homeostatic and circadian sleep drives in fatigue is also explicitly accounted for.

People do not consciously weigh demands against resources, because to do so requires that they know what their resources are in relation to the perceived demands. Growing awareness of bodily sensations related to weariness and weakness is more likely, which causes increasing desire to withdraw from the task, decrease performance or otherwise cope. Feelings may be emotional such as negative emotions associated with fatigue e.g. listlessness, flatness, or they may be sensations in the body such as weakness or sleepiness. Overall the feeling will be reported as one of tiredness or fatigue. In this process the person may not be aware of their own cognitions, but there may be thoughts related to the importance and value of higher order goals, and about the options available to the individual to preserve those goals. If the experience of fatigue is not new the individual will be more likely to rely on past schemas formed from value judgments. As the process progresses, the individual may perceive that "fatigue" feelings are growing stronger or attention may be increasingly directed to those feelings. Such feelings will increasingly trigger thoughts about coping, resting or withdrawing, and where coping options are limited, lead to stress and strain if the person is motivated to carry on. This process will also be informed by performance feedback.

In addition to task effects we should consider the longer term effects of fatigue on performance when a range of work activities is performed. Psychological detachment from work on the evenings or weekends (Demerouti et al., 2012), or regularity of sleep and its role in self-regulation (Barber & Munz, 2010), may also play an important role in building fatigue. In real jobs, these activities are complex and both physical and mental. The extent to which such factors are considered by models covered so far is at best limited. For a treatment of these factors, the reader is referred to section 7 of this report, and the report by Phillips & Bjørnskau (2013).

6 How should we measure fatigue?

Chapter 4 explains that even though fatigue is best captured by considering its experiential, physiological and performance aspects, many past studies have operationalized fatigue using narrow definitions of fatigue. One consequence of this is that there has been a tendency for single measurements to act as representative of fatigue. At the same time measurements have tended to reflect the particular interests of the researcher. For example, clinical researchers have been more interested in self-reports and managers more interested in performance (Christodoulou, 2012). If the measurement of fatigue is to be consistent with proper operationalization, we argue that several dimension should be measured in order to understand the status of, influences on and effects of fatigue, independent of researcher interests. This section therefore considers how each fatigue dimension can be captured either by self-reports (experiential aspects) or observations (physiological and performance aspects).

It is informative to start an overview or taxonomy of fatigue constructs given by Matthews et al. (2012), which in Figure 4 has been expanded to account for performance aspects.

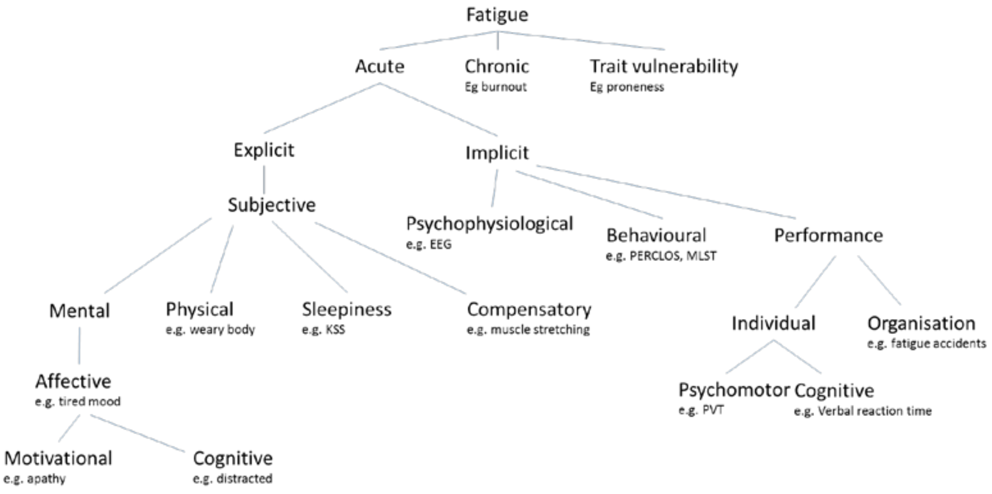

Figure 4. Taxonomy of fatigue constructs expanded to account for performance dimension.

Figure 4 shows that many different constructs can be used to capture fatigue, and there are several ways to categorize these constructs. It also illustrates the greater focus there has been on measuring acute rather than chronic fatigue, even though it is not clear whether chronic fatigue is any less important, either in terms of health or performance.

The most frequently used measures of acute fatigue in the literature are subjective measures. These are considered by some as explicit, in the sense that asking respondents how fatigued they are is the most direct way to tap into fatigue.

6.1 Subjective measures

Subjective ratings of fatigue have been criticized as being poorly sensitive, i.e. studies suggest performance decrements may be exponentially related to subjectively felt increases in fatigue (Dawson & McCulloch, 2005) (Pilcher & Walters, 1997). However, as we have seen, the sensation of fatigue is being seen as increasingly important as a determinant of compensatory behaviour, downstream performance decrements (latent performance), and health decrements. These indicators may be as least as important as actual performance in terms of fatigue-related *risks* to the performance of the human transport operator. It is therefore still important to measure subjective fatigue.

Subjective measures are available that exclusively measure sleepiness, as well as others that tap into the broader fatigue construct. The latter are often attempts to measure mental fatigue, which typically comprises cognitive, motivational and general fatigue aspects. Over 30 measures have been developed and tested for the measurement of fatigue by self-report. One implication of this is that it is often difficult to compare reports of subjective fatigue, since they often do not use the same fatigue measure. Despite this, it has been noted that greater integration has been achieved on research programs aimed at assessing subjective fatigue than cognitive performance fatigue (Ackerman, 2011).

Some authors employ single item questions and ask respondents to consider their fatigue across different time periods, e.g. “Did you have low levels of energy, poor sleep, or a feeling of fatigue in the past 2 weeks?” (Ricci et al., 2007); “With what frequency have you felt fatigue in the last 3 months?” (Ho et al., 2013). Others assess fatigue using an item battery with Likert-type response scales, which is psychometrically superior. For example, Loge et al. (1998) assesses fatigue using 11 items in which the sum score of responses is used. Still other authors use visual analogue scales (VAS), where the respondent is asked to rate fatigue along a continuous line, with each end of the line anchored by opposing descriptions of a fatigue state (e.g. Monk, 1989; Lee et al., 1991). VAS are respondent friendly, sensitive and very amenable to modern survey technology. The drawback is that interpretation of scales may be highly subjective, and they may thus be best suited for within-subject comparisons (Shen et al., 2006).

There are several comprehensive reviews of questionnaires used to assess fatigue and sleepiness in medical and general populations, which detail different forms of reliability (Christodoulou, 2012; Dittner et al., 2004; Shahid et al., 2010). It is not our intention to repeat these in full here, but examples of scales and associated characteristics are provided in Table 3 to illustrate the range available. Initially there was a tendency to capture fatigue within general health or mood surveys (POMS; WHOQOL; Short Form Health Survey, SF-36) (Ware et al., 2002), but now several scales have been developed aimed at measuring specifically fatigue.

6.1.1 Popular scales for measuring fatigue

The seven most common fatigue scales are probably the Fatigue Severity Scale (FSS), Chalder's Fatigue Scale (CFS, also known as the Fatigue Questionnaire), the Multidimensional Fatigue Inventory (MFI), the Fatigue Impact Scale (FIS), the Brief Fatigue Inventory (BFI) and the VAS for Fatigue (VAS-F) (see Table 3). Each of these has good psychometric properties (Dittner et al., 2004).

The FSS is probably the best known and most used, by both clinicians and researchers interested in healthy people, supported by its good test-retest reliability, concurrent validity, ability to distinguish disease-specific symptom profiles, and favourable comparison with the CFS (Dittner et al., 2004). Part of the reason that it is used for assessing healthy respondents is that it evaluates the effect of fatigue on specific types of functioning, relating to the behavioural consequences of fatigue, rather than its symptoms (Shen et al., 2006; Shahid et al., 2010). The FAI and FIS are also popular among clinicians. The FAI is suitable for assessing qualitative and quantitative aspects of fatigue in medical patients, while the FIS is used more to assess impact of fatigue on cognitive, physical and psychosocial functions (Shahid et al., 2010). The CIS is notable because it is well validated in medical patients (good internal consistency, split-half reliability) and has been used successfully to distinguish fatigued from non-fatigued workers, and show changes in fatigue over time. The MFI is notable for its comprehensiveness i.e. it appears to capture all aspects of fatigue. However, it is not clear whether criticisms of some surprising results and of its subscale structure have been addressed (Dittner et al., 2004). In this respect, the MFSI may be more promising (see Table 3). This is also comprehensive, and since it contains no reference to medical diagnosis, may be useful for assessing fatigue in healthy populations.

Table 3. A selection of self-report scales for measuring subjective fatigue.

Name and Acronym		Subscale description	Items	Example	Comments	Reference
Chalder's Fatigue Scale / Fatigue Questionnaire	CFS / FQ	Mental Physical	8 6	Do you have problem with tiredness? Do you have difficulty concentrating?	Measures severity of fatigue in primary care. 4-point Likert response scale.	(Bailes et al., 2006; Chalder et al., 1993)
Swedish Occupational Fatigue Index	SOFI	Sleepiness Physical discomfort Motivational Energy Physical exertion	5 5 5 5 5	Not available	Measures fatigue aspects that vary among occupational groups. 11-point response scale.	(Åhsberg, 2000)
Maslach Burnout Inventory, Emotional Exhaustion subscale	MBI-EE	Emotional Exhaustion	5	Asks about preceding 2 weeks.	For assessing longer term effects of fatigue. Good psychometrics. 7 point rating, from 1 = never to 7 = always-	(Maslach, 2000; Michielsen et al., 2003)
Fatigue Severity Scale	FSS	One general scale	9	My motivation is lower when I am fatigued; I am easily fatigued; Fatigue interferes with my physical functioning	Impact and functional outcomes related to fatigue (not severity!) 7-point Likert from completely disagree to completely agree	(Krupp et al., 1989)
Fatigue Assessment Instrument	FAI	Severity Situation specificity/causes Psychological consequences Response to rest	29 total	I am easily fatigued Exercise brings on my fatigue When I am fatigued, I have difficulty concentrating. Resting lessens my fatigue.	Expanded version of the FSS, only moderate test-retest reliability. Asks about preceding 2 weeks.	(Shahid et al., 2010)
Multidimensional Fatigue Inventory	MFI	General fatigue Physical fatigue Mental fatigue Reduced motivation Reduced activity	5 5 5 5 5	Physically I feel able only to do a little	Good internal consistency and test-retest reliability for all scales. Questionable structure fit. 7-point scale from yes, that is true to no, that is not true.	(Watt et al., 2000; Smets et al., 1995)
Multidimensional Fatigue Symptom Inventory	MFSI	Global fatigue		Not available.	Factor analysis shows good structure fit, other psychometrics good.	

Name and Acronym		Subscale description	Items	Example	Comments	Reference
		Somatic symptoms Cognitive symptoms Affective symptoms Behavioural symptomes				
Multidimensional assessment of fatigue	MAF	General (10-point response scale)	16	How severe is the fatigue you have been experiencing? To what degree has fatigue caused you distress?	Assumes people know whether they are fatigued or not. Over 1 week.	
Fatigue Assessment Scale	FAS	Single fatigue scale derived from the CIS, MBI and WHOQOL-EF.	10	I am bothered by fatigue.	Good internal consistency, no cross loading with emotional stability scales.	(Michielsen et al., 2003)
Fatigue Impact Scale	FIS	Cognitive impact Physical impact Psychosocial impact	40 total	Not available	Good internal consistency, good for assessing impact on people's lives, but assumes they have fatigue.	(Shahid et al., 2010)
World Health Organisation Quality of Life-Energy Fatigue	WHOQOL-EF	Energy Fatigue	2 2	Two positively phrased items Two negatively phrased items	Good psychometrics; high correlation with POMS	(Michielsen et al., 2003; Power et al., 1999)
Profile of Mood States – Fatigue	POMS-F	Moods	65	Not available	Good Psychometrics. Completed within 5 min	(McNair etal., 1992)
Piper Fatigue scale	Piper-FS	Temporal Intensity Affective Sensory	-	41 items in total on a visual analogue scale, mainly clinical use.	Criticised for item wording, questionable psychometrics	(Dittner et al., 2004)
Patient-reported Outcome Measurement Information System Fatigue Item Bank	PROMIS-FIB		-	Not available		(Lai et al., 2011)
Profile of Fatigue Related Symptoms	PRFS		-	Not available		(Ray et al., 1992)

Name and Acronym		Subscale description	Items	Example	Comments	Reference
Checklist Individual Strength	CIS	Subjective fatigue Concentration Motivation Physical activity	8 5 4 3	I feel tired Thinking requires effort I am full of plans I feel in good shape	7-point Likert, from yes that it true” to “no that is not true”	(Beurskens et al., 2000)
Category Ratio Scale	CR-10	Verbal descriptors		Not available	Descriptors anchored on 10 pt scale.	(Borg, 1982)
Brief fatigue Inventory	BFI	Fatigue severity	9	Not available	Developed for screening cancer patients for fatigue. 11-point Likert.	(Mendoza et al., 1999)
Driving fatigue scale	DFS	Muscular fatigue Exhaustion-sleepiness Boredom Confusion-distractibility Performance worries Comfort seeking Self-arousal	-	Having tremors in my limbs Fighting myself to stay awake Find driving repetitive I’m easily distracted I’m losing track of where I am I just want to take it easy Listening to the radio		(Matthews et al., 2012)
Visual analog scale - Fatigue	VAS-F	Energy Fatigue	-	Not at all active-extremely active Not at all tired-extremely tired	Good psychometrics, correlates with POMS and SSS. Morning Energy score correlates with evening Fatigue score. Able to distinguish sleepiness and fatigue?	(Dittner et al., 2004; Lee et al., 1991)
Toronto Sleepiness and Fatigue Scale	TSFS	-	-	Not available		(Shahid et al., 2010)
Karolinska Sleepiness Scale	KSS	Situational sleepiness	1	Similar to SSS below	Much studied in transport research, and often links to operator performance. 9-point description-anchored scale	(Åkerstedt, 1990)
Stanford Sleepiness Scale	SSS	Situational sleepiness	1	Score 1 to 7 on scaled anchored from “feeling active and vital; alert; wide awake” to “sleep onset soon; lost struggle to stay awake”.	Similar to KSS, may be more popular outside Europe.	(Hoddes et al., 1973; Johns, 1991)

Name and Acronym		Subscale description	Items	Example	Comments	Reference
Epworth Sleepiness Scale	ESS	General sleepiness	8	Sitting and reading; Watching TV; As a passenger in a car.	Score across eight situations varying in soporific nature over past few weeks. Score 0 (= I never doze off) to 3 (high chance of dozing off).	(Johns, 1991)
Toronto Hospital Alertness Test	THAT	Alertness	10	Score from 0 (= not at all) to 5 (=always) on past week e.g. fresh, energetic, able to concentrate, think of new ideas, feel extra effort necessary to maintain awareness)	Measure influence on alertness of sleep loss, holiday; and proportion of day associated with alertness. High internal consistency, alpha = .96.	(Shapiro et al., 2006)
	ZOGIM-A	Alertness	10	Score from 1 (= extremely) to 5 (= not at all)	Measures impact of influences on (sleep loss, exercise, holiday etc.) and anticipated benefits of alertness (ability to organize and preempt, task completion, creativity etc.). High internal consistency = .83.	(Shapiro et al., 2006)
Fatigue, Anergy, Consciousness, Energized, Sleepiness.	FACES	Fatigue Anergy Consciousness Energized Sleepiness	50 total	Weary Indolent Dormant Full of pep Snoozy	Respondents identify with one word adjectives, some of which may be difficult to understand	(Shapiro et al., 2002)
Sleepiness Symptoms Questionnaire	SSQ	Sleepiness symptoms and performance	8	Struggling to keep eyes open; Reactions were slow	Moderate test-retest reliability. Specific items relate to either driving performance or EEG sleepiness indicators. 7-point response scale.	(Howard et al., 2014)

Subscales of fatigue scales reflect that the experience of fatigue is multidimensional

Unidimensional scales can be practically useful when there is limited space on a questionnaire, and most have good validity. However, for assessing the qualitative differences in aspects of fatigue, multidimensional scales are necessary (Dittner et al., 2004). The sensation of fatigue itself has been found to break down statistically into several dimensions. (Wolf, 1967 cited in Ackerman, 2011) found three core feeling dimensions, which were nervousness, drowsiness/sleepiness, and exhaustion, while others report drowsiness/sleepiness, difficulty concentrating and bodily complaints (Kogi and colleagues cited in Ackerman, 2011). The principal components analysis carried out in developing the Profile of Fatigue Related Symptoms indicated that scores varied according to whether fatigue was experienced emotionally (e.g. sadness, pleasantness, tenseness), cognitively (e.g. hard to concentrate, slowness of thought), or physically (e.g. heavy limbs, muscular weakness) (Ray et al., 1992). In an occupational health context, three dimensions have been reported: drowsiness, physical fatigue or exertion and thinking/concentrating fatigue (Yoshitake, 1978). The physical and drowsiness dimensions of fatigue may be the most commonly noted (Åhsberg, 2000). A motivational dimension (e.g. apathy, indifference, withdrawal) has also been found to be important (e.g. SOFI, CIS, MFI in Table 3). Finally, when asked to give symptoms of mental fatigue, people refer to interference in cognitive performance e.g. poor concentration, difficulty making decisions and sluggish thoughts, rather than emotion (Bentall et al., 1993).

Thus, sleepiness, cognitive and physical fatigue and to some extent emotional aspects are commonly distinguished sub-dimensions of fatigue scales. This dimensionality of the *experience* of fatigue, adds another layer of complexity to our operationalization of the term. In particular, it implies that we should be careful about reports of lack of alignment between self-reported fatigue and performance. Is there lack of correlation between all subscales and performance, or just some? Do some subscales relate more closely to behaviour or performance? Of course, even if there is no correlation with performance for particular subscales, there is still a need to capture subjective fatigue as an important index in understanding the total effect of fatigue on increase in effort and deterioration in performance.

An overarching dimension of general fatigue

Independent of particular subscales, all share substantial variance with one single overarching fatigue dimension, and notably a single overall score on the CIS also predicts occupational accidents and sickness absence (Janssen et al., 2003; Swaen et al., 2003). Indeed, although developed as multidimensional, to CIS was found to have high unidimensionality on independent testing in occupational groups (DeVries et al., 2003). The explanation for mixed findings of factor analyses of uni- and multi-dimensionality is probably explained by an overarching dimension of fatigue that the subscales share. This was recognized statistically in development and validation of the SOFI scale, whose subscales are nested within an overall scale, labeled “lack of energy” (Åhsberg, 2000).

Important to define period over which fatigue is measured

Unlike sleepiness scales, which are clearly divided into those which measure acute and global levels (Cluydts et al., 2002), fatigue scales have been criticized for failing to clearly denominate how long the period of fatigue has lasted (Christodoulou, 2012). Thus, for example, the CFS item “Do you have difficulty concentrating?” implies that the respondent should generalize over an unknown period. Where a scale asks the respondent assess their fatigue over a defined period, this can be seven days or longer. This is important, because measurement of people's momentary fatigue in their natural environment, for instance using mobile phone apps, results in ratings of fatigue that are lower than recalled fatigue (Broderick et al., 2009). Respondents may have difficulty recalling the continuous stream of symptom experiences and with creating a rating that is representative of the average of those experiences (Stone et al., 2007). Fortunately for researchers not wishing to be too invasive, end-of-day ratings of a 5-item fatigue measure (comprising four SF36 and one BFI item) have been found to act as an extremely good proxy for momentary ratings averaged across the day, and the average of three to five end-of-day ratings correlates strongly with a week of momentary ratings (Broderick et al., 2009). End-of-day ratings will, however, not be able to capture any intraday variation in fatigue caused by sleepiness factors.

Sleepiness scales are well developed and validated

A popular self-report instrument for assessing sleepiness is the Karolinska Sleepiness Scale (KSS), in which respondents can choose one of seven items describing increasing sleepiness that best describes their current subjective state (Åkerstedt, 1990). The KSS has high correlation with time of day. The Stanford Sleepiness Scale is closely analogous (Table 3). The Epworth Sleepiness Scale (ESS) is more akin to trait measure of global sleepiness, since it asks respondents to rate global tendency to fall asleep in different situations across several weeks. The sleep-wake activity inventory (SWAI) is similar, but it also measures nocturnal sleep onset (Rosenthal et al., 1993) (Shahid et al., 2010). The ESS and SWAI scales will thus not capture the intraday circadian or homeostatic variations in sleepiness described by the two-process model of sleep. Both scales have good psychometric properties (Cluydts et al., 2002).

Few fatigue scales treat sleepiness and fatigue as two separate but interactive processes. However Bailes et al. (2006) attempted to construct two scales for the non-confounded measurement of sleepiness and fatigue, for clinicians who wanted to better distinguish fatigue that is not sleepiness, since the former thought to be underdiagnosed and poorly treated. Responses on existing fatigue questionnaires (FSS, CFS) and sleepiness questionnaires (SSS, ESS) were factor-analysed to generate two scales which only minimally correlated, and which represented distinctive patterns of association. Two new scales were generated, the "Empirical Sleepiness Scale", containing seven items on a 6-point Likert agreement scale, limited to experiences of daytime sleepiness, and the "Empirical Fatigue Scale", containing 4 items and associated with broader insomnia and psychological maladjustment. The Toronto Sleepiness and Fatigue Scale also measures sleepiness and fatigue concurrently (Shahid et al., 2010).

Sleep diaries usefully complement fatigue and sleepiness scales

Sleep diaries are a very useful supplement to subjective reports of fatigue and sleepiness in field studies. Participants are often asked to record a log of sleep and wake times (and/or go-to-bed and get-up times) every day for a defined period, alongside their responses on sleepiness / fatigue scales, and any other influencing factors of interest, such as diet, time at work, abnormal situations, time in and out of port (seafarers) or loading/unloading and so on. The use of sleep diaries in studies of human transport operators will be discussed in more detail in a separate report to be issued by the Fatigue in Transport project.

Alertness has been overlooked in studies of human transport operators

Rather than the sleepiness component of fatigue, alertness may be more closely linked to optimal human transport operator safety performance, since lack of alertness may be more common than sleepiness. Alertness and sleepiness are not opposites of the same scale i.e. alertness is not wakefulness, and the two states have been shown to have distinct neurology (Shapiro et al., 2006). Only two questionnaires have been developed to measure alertness. The Toronto Hospital Alertness Test (THAT) is designed to measure perceived alertness in the past week, while the ZOGIM-A is designed to measure the impact of various influences on and anticipated benefits of alertness (see Table 3). Neither scale correlates with objective wakefulness, supporting that subjective alertness is not simply the absence of sleepiness, i.e. it is possible to feel a low level of alertness and yet not be sleepy. This may be an important and overlooked aspect of fatigue-related performance for human transport operators.

6.1.2 Measuring fatigue in working populations

Assessment of fatigue in working populations is often performed as part of an overall health assessment, with the result that single items are used and it is often measured poorly. For example, a recent article uses one item to assess frequency of fatigue over the past three months (Ho et al., 2013). However, there are a number of exceptions. The 20-item CIS (see Table 3) has been used to assess fatigue in workers for the Maastrich cohort study. Each item was scored on a 7-point Likert scale and fatigue rated if the total score for all items was greater than 76 (Kant et al., 2003). The CIS was shown to distinguish between fatigued and non-fatigued persons in occupational groups (Beurskens et al., 2000). A set time period of two weeks was used. Secondary outcomes recorded were general health (GHQ12), need for recovery (van Veldhoven & Broersen, 2003) and the Maslach Burnout Inventory (Maslach, 2000). The CIS has also been developed in other studies of occupational groups. Although often used in connection with a health focus, the CIS is a robust measure of fatigue in working populations (Bültmann et al., 2002).

The Swedish Occupational Fatigue Inventory, or SOFI (Åhsberg, 1998), is considered the most developed occupational scale (Table 3). It has five subscale: lack of energy, physical exertion, physical discomfort, lack of motivation and sleepiness. These subscales map onto overarching scales for general, physical and mental fatigue (Åhsberg, 2000). As part of its development, participants worked on a 2 x 90-minute vigilance and 2 x 90-minute proof-reading task. Responses on the SOFI were compared to task performance. Scores were also compared with responses on Borg's CR10, as well as the following physiological measures: blood pressure, heart rate, heart rate variability and muscle activity. The mental dimension of SOFI was validated in the sense that there was a high correlation between task performance and post-task scores on SOFI indicating lack of energy, lack of motivation and sleepiness, particularly following the vigilance task. Physical tasks correlate poorly with mental fatigue as assessed by SOFI. There was high correspondence with the CR10, but little correlation was found between physiological measures and ratings, as reported by several other authors.

Following laboratory experiments, the SOFI was validated in a field study by asking workers at a paper mill to fill out the SOFI, KSS (sleepiness), time worked and reaction time performance (Åhsberg, 1998). Participants expressed their fatigue primarily in terms of sleepiness, which is typical for shiftworkers, but lack of energy and lack of motivation was also captured as an important part of their fatigue experience. Importantly there was good correlation with reaction time and mental scales on the SOFI. In a subsequent article the usefulness of the SOFI subscales was validated by comparing fatigue in different occupational groups, and the response scale revised (Åhsberg, 2000). The hypothesis was that teachers, firemen, cashiers, bus drivers and shift workers (train drivers) would all score highly on the overall “lack of energy” scale, but that the subscales would distinguish the different occupational groups. Firemen were expected to score high on “physical exertion”, cashiers high on “physical discomfort”, bus drivers high on “low motivation”, and shift workers high on “sleepiness”. The results fitted well with this hypothesis, suggesting that a unidimensional fatigue construct is insufficient to describe fatigue in different occupations. SOFI appears to be relatively culturally robust, having been validated in the USA (Muller et al., 2007) and with Chinese VDU operators (Leung et al., 2004). A Spanish validation also proved successful, although here it was necessary to reduce the 25 items to 15, while maintain the original scale structure, i.e. several dimension of fatigue and one latent “lack of energy” factor (Gutiérrez et al., 2005).

Other notable instruments used in for studying workers are the FSS, used to distinguish fatigued and non-fatigued shiftworkers (Hossain et al., 2003), and Kashigawi’s (1971) study of assessing fatigue according to how tired a worker appears to his or her colleagues. Of note for the study of fatigue in occupational groups is that the experience of task-related fatigue has been characterized by Matthews (2012) as especially associated with loss of motivation, mind wandering, emotional distress, specific patterns of physical discomfort, and attempts at coping. Dimensions for fatigue that are specifically task-related have also been identified as task engagement, distress and to a lesser extent worry.

An important final point on assessing fatigue in occupational groups is that there may be a need to consider how job tasks and activities may be sensed as fatigue in ways that will not be assessed by generic reporting instruments. For instance, after four hours of work, VDU operators typically report discomfort of the eyes, neck, and shoulders, more than for the legs, lower back, wrists or elbows (Leung et al., 2004). Such an assessment of local physical effects is not often done when assessing fatigue, but may be indicative of effort and thus particularly informative for human transport operators. Specific assessment of physical fatigue patterns would help characterize fatigue problems specific to certain types of human transport operator, and usefully complement instruments like the SOFI, which is able to distinguish occupations according to their general, mental and physical fatigue patterns.

Subjective reports of job-related activities and compensatory strategies

The FSS and FIS measures we have already covered, are multidimensional in that they include an assessment of fatigue impacts on functioning and behaviour. This underlines the point that subjective reports can be used to assess the feeling of fatigue as well as its effects on performance. In fact the latter may be perceived by respondents as part of the experience of fatigue. Self-reports on certain task- or job-related activities of human transport operators, safety behaviours or cognitive performance, may all be collected in order to measure fatigue. Examples of instruments that can be used generically are the Cognitive Failures Questionnaire where someone scores from 0 (=never) to 4 (=very often) on items such as “Do you fail to notice signposts on the road?” or “Do you lose your temper and regret it?” (Broadbent et al., 1982), or the Driver Behaviour Questionnaire (Reason et al., 1990; Özkan et al., 2006). The Sleepiness Symptoms Questionnaire (SSQ) is a new scale developed in a simulator specifically to allow drivers to recognize symptoms that are directly related to reduced driving performance (Table 3); it has moderate test-retest reliability. In many cases it may be preferable to carry out tailor-made assessments of behaviours or aspects of cognition that may be vulnerable to fatigue and important for safety in a particular role type. (A consideration of the safety-related functions of human transport operators that may be vulnerable to fatigue is given in Section 7.) Finally, an important consideration when collecting subjective performance data is whether they are collected as the job is performed or whether a defined period is reviewed. An example of the former is measurement of increased resistance against further effort in relation to time into task (Meijman, 2000). These measurements also typically include constructs of exertion, such as perceived effort, effort expended and discomfort (Pearson & Byars, 1956).

Compensatory activities used by car drivers that also indicate they are fatigued have also been measured, such as winding down the window or stopping to stretch their legs (Hanks et al., 1999; Nordbakke & Sagberg, 2007). Strategies used by watch-keepers at sea or locomotive engineers have not been studied as systematically, as far as we are aware.

6.2 Objective measurement

It is often stated that there is no direct, objective measurement of fatigue. Instead the presence of fatigue must be implied from objective measurements of behaviour, physiology or performance. Some of these objective measures are described here. Many focus only on sleepiness, since this aspect of fatigue can be measured objectively.

6.2.1 Measures of physiology

Although invasive and resource intensive, polysomnography (electroencephalograph [EEG], electroocculogram, electromyogram) has been used to measure sleepiness objectively in applied research, in simulators and in work settings. In one study 20 per cent of subjects performing night work in a papermill were found to have slept using polysomnography (Torsvall & Åkerstedt, 1988). Episodes of drowsiness, microsleeps or sleep during monotonous work tasks were reflected by increased alpha and theta activity and slower eye movements.

Sleepiness can also be measured using pupillometry (Cluydts et al., 2002). Less direct ways to measure sleep include behavioural observations of yawning frequency, eye movements, tired eyes, blink rate, percentage eye closure (PERCLOS), head movements, and facial expressions, and measurements of heart rate or heart rate variability (Craig et al., 2011). PERCLOS, eye movement and facial tone showed great promise as measures of implicit fatigue in simulator studies, especially when used alongside task-related performance measures such as lane drift and steering movements in driving (Knipling, 1998). Some of these measures have already been employed in naturalistic observation studies (Kecklund, 2009). PERCLOS in particular has proved a promising correlate of fatigue in pilot projects (Wilschut et al., 2009) and PERCLOS sensors are being commercialized by several companies. For example, CoPilot (Attention Technologies, PA, USA) is a dashboard-mounted camera that monitors and gives driver feedback on percentage eye closure by detecting infrared reflected from the retina (Dinges et al., 2006). Optalert is a similar device made in Australia by Sleep Diagnostics. Technology to detect changes in face muscle tone as an indicator of fatigue are also being developed (Caldwell et al., 2009). Systematic behavioural observations are proving useful in the analysis of naturalistic driving events, and are forming the basis of new technology to monitor operator sleepiness, since they are closely linked to performance in events of sleep behind the wheel (Backer-Grøndahl et al., 2009). Bench-top or portable devices are available that monitor pupil characteristics to give instant estimates of driver alertness (e.g. PMI Inc's FIT2000/2500) (Gertler et al., 2002; Heitmann et al., 2009; Shahid et al., 2009) These devices require further validation to show that they measure what they purport to measure. Cardiovascular variables and stress hormones are often used in workload research (Hockey, 1997). Catecholamine and cortisol increase in response to vigilance performance in a wide variety of situations, indicating a stress response (Hancock & Warm, 1989). Finally, some attempts are ongoing to combine different psychophysiological measures in order to increase reliability of individual measures (Bowman et al., 2009).

6.2.2 Measures of sleep propensity and sleep behaviour

Most systematic development of behavioural measures of fatigue concerns sleepiness, and measure actual sleep propensity. Empirical techniques such as the multiple sleep latency test (MSLT (Bonnet & Arand, 1998)) and the maintenance of wakefulness test (MWT (Mitler et al., 1982)) involve instructing participants to lie down in a dark room and either resist or not resist falling to sleep. In the MSLT four or five nap opportunities are given every 2 h beginning 1.5 to 3 h after waking. A sleep latency of 10-15 minutes, for instance, indicates mild sleepiness. In the MWT the participants are asked to sit up in bed in a dark room every 2 h and remain awake. The time taken for sleep to occur is seen as a measure of sleepiness. The MSLT is thought to be more a measure of the sleep drive, and MWT the wake drive or arousal (Shen et al., 2006). These tests have low ecological validity (local conditions are optimal for sleep), involve the use of invasive polysomnography, and are expensive and inefficient in terms of respondent numbers generated. There is poor correlation between SSS and the MLST (Shahid et al., 2010). This is not surprising given that SSS measures acute and MSLT measures global sleepiness. However, the lack of correlation between ESS and MSLT is more surprising, and may reflect other reports of dissociation between subjective and physiological indicators of sleepiness.

The main use of objective tests of sleep propensity and wakefulness is in studying sleep structure and clinical disorders, such as narcolepsy, rather than human transport operator research (Cluydts et al., 2002). A far more practically useful objective measure in terms of transport operations is the actigraph. An actigraph is a wrist-worn computer containing an accelerometer to record movements correlated with sleep/wake activity (Sadeh & Acebo, 2002). While actigraphy may be a more indirect measure of sleepiness than latency tests, it nevertheless supplements fatigue studies with very useful information that can help interpret other subjective and performance measures collected. Validity, reliability and limitations of actigraphy for documenting sleep-wake patterns have been addressed. Actigraphy has helped document the effects of various behavioral and medical interventions on sleep-wake patterns, although it is of limited use for documenting sleep-wake in individuals who have long motionless periods of wakefulness (e.g. insomnia patients) or who have disorders that involve altered motility patterns (e.g. sleep apnea). Actigraphs are now readily available at relatively little expense (e.g. www.sleepwatch.com, www.jawbone.com, www.fatigeuscience.com), although the extent to which each has been validated must be checked. Sleep scores recorded by an actigraph can be input into sleep models to predict sleepiness risk, or used to inform managers or drivers about the amount of sleep drivers obtain. They can also be useful in the evaluation of company interventions aiming to improve driver sleep.

6.2.3 Measures of performance

Fatigue is understood by some to result in a decrease in operator resources available to the task and increased effort required to perform the tasks. Others claim that fatigue is only distantly indicative of resource depletion, or rather indicative of goal discrepancies (see Section 4). In either case a fatigued state is thought to have varying implications for individual effort and performance. To understand fatigue fully, we thus must understand what happens to performance by measuring it, subjectively, objectively or preferably both (Baker et al., 1994).

The effects of sleep loss on metabolic activity within the prefrontal and parietal cortices have consequences for a wide range of cognitive functions, mainly via effects on the prefrontal cortex (Kilgore, 2012). The implications of this for performance are wide and varied, and many measures used for assessing cognitive and related psychomotor performance decrements have been developed. These are summarized by (Curcio et al., 2001), and an impressive review of over 50 tests for attention, working memory, long-term memory, visual-motor performance, decision making, verbal functions, response inhibition, and other measures is given by Alhola and Polo-Kantola (2007). The various effects of fatigue on objective performance are also reviewed in Section 7 of this report.

Tests for objective cognitive performance can be classified as to whether they are based on attentional tasks; memory tasks; or logical reasoning tasks (e.g. algebraic or language tasks). Widely-used attentional tasks often involve a visual search (Mackworth, 1950), which form the basis of many palm-top tests. Tools for assessment of cognitive ability and information-processing in the context of fatigue are listed by (Ackerman, 2011), according to what they assess, as follows:

- Reaction time
- Change in number of items attempted in a certain time
- Patterns of errors over time (fatigue can induce errors, which when they do occur are followed by more and qualitatively different errors)
- Quality of responses (fatigue can induce increase in need for cognitive closure, or changes in judgment during extended task performance)
- Changes in riskiness of responding (shift from purposeful to random responding)

Psychomotor tests involve reaction time tasks (acoustical, visual, multiple choice), tracking tasks, tapping tasks or a combination of these. For example, the Wilkinson Auditory Vigilance Task asks respondents to push a button when they hear brief sound randomly emitted among a series of longer ones. Performance is based on hits, omissions and false positives. Since it lasts 30-60 min it has been superseded by shorter Simple Reaction Time Test (10 min; Glenville et al., 1978). Another example is the Four-Choice Reaction test (Wilkinson & Houghton, 1975), in which the correct button corresponding to one of four lights that light up in a random series must be pressed. A tracking task involves tracking using a mouse to follow a moving object on the screen, while a tapping task is based on self-generated motor responses e.g. respondent asked to hit a button continuously and repetitively with finger and inter-tapping interval variability a measure of sleepiness. Tracking and tapping tasks are very sensitive to sleepiness (Curcio et al., 2001).

A time has gone on, all of these tasks have become less simplistic and computer-based. Several different psychomotor vigilance task (PVTs) may now be carried out in the field on small palm-top computer devices, either before or during the duty of the human transport operator. A classic PVT is a test where participants must press a button whenever a light appears at random intervals, over the course of 5 to 10 min (Balkin et al., 2010). Increase in the use of the PVT may be because it is seen as set of specific measures of response lapsing and slowing, i.e. a test of functions most prone to fatigue (Kribbs & Dinges, 1994). PVTs have been used as a relatively robust objective measure for the evaluation of fatigue programmes (Phillips & Sagberg, 2010a). PVTs have already proved useful in operational assessments of the effect of different rosters on fatigue in the field (Jay et al., 2005), although further validation under operational conditions is desirable.

Studies using the measures described here are numerous, but there has been a focus on individual differences at the expense of mean variation in these measures with fatigue (Ackerman, 2011). Another criticism is that performance ratings of many tests will be very specific to the task and conditions in which the task is performed.

Task- and job-specific performance

One way to address this is using simulators, which are available for rail, road and sea operations. In car drivers, for instance, there is increased standard deviation of lateral position with fatigue, as well as increased variation in longitudinal position (adaptation to position of other cars requires perception and attention and headway therefore is also influenced by fatigue).

A combination of performance measures may be required to completely assess the effects of fatigue on job-related performance. This is illustrated by a study showing that performance in proof-reading *improves* over the day in terms of total detected errors and number of pages read (Åhsberg, 2000). However, the number of errors per page detected decreased, and the type of error also changed (more typos, less grammatical errors detected indicative of less active proof-reading). In other words, respondents appeared to change their reading strategy in response to fatigue, i.e. they read faster but more carelessly in the afternoon than in the morning. Such changes may relate to compensatory behaviour described by Hockey (1997).

6.3 Measuring the effects of compensatory activity

Health measures

Longer-term health outcomes may be the result of attempts to cope or compensate in order to maintain task performance in the face of fatigue. Measuring health is therefore an important part of understanding the effects of fatigue on employee health, which has been found to have latent performance implications (Phillips & Bjørnskau, 2013; Taylor & Dorn, 2005). Insufficient sleep arising as a result of long-term shift work may be an important factor in the poorer health outcomes also associated with shift workers e.g. (Phillips & Sagberg, 2010; Wagstaff & Lie, 2011), and psychological problems have been reported as the consequence of sleeping problems in bus drivers (Kompier, 1996b). Health problems may not always be due to lack of sleep *per se*, but attempting to work in the face of sleep deprivation. Note that there may be a cyclical relationship between poor health and fatigue, in which performing the task while fatigued or stressed leads to poor health, which in turn exacerbates fatigue and so on (de Lange et al., 2009). For long-term duty fitness the interaction between fatigue and stress may also be important to consider. Those drivers who are continuously stressed by the job and experience sleep pressure from work schedules over a prolonged period will eventually enter a vicious circle, where psychological problems caused by the interaction of (i) stress on the job and (ii) fatigue from schedule-restricted sleep will only serve to exacerbate sleep difficulties, reducing further ability to cope with stress, and so on. A key question is what effects such a synergistic interaction will have on safety performance in the long term.

Other job functions

According to the CCM there may be latent performance decrements in terms of post-task prioritisation of low-effort activities. Thus, while there may be no change in performance of the main task, fatigue may result in less or simpler work being done beyond the main task.

Organisational measures

Over the longer term fatigue in a workforce may affect organisational outcomes connected with health and wellbeing, such as health records, driver absence and employee turnover, lost productivity, increased wear and tear on equipment, and fatigue-related accident or near miss analyses (Gertler et al., 2002).

It is notoriously difficult for accident investigators to identify fatigue as a cause of an incident or accident in the absence of a definitive post-crash marker of operator impairment, and there have been several calls to improve the way police and employee organisations collect data in order to ease identification of fatigue factors (Arnold & Hartley, 1998).

6.4 Summary

Although not related directly to objective performance, subjective measures of fatigue are valuable since they may better relate to compensatory effort, health and stress effects, and downstream performance decrements. In collecting self-reports, however, it is important to state the period over which the respondent should consider his or her fatigue.

There are over 30 scales for measuring subjective fatigue, six or seven of which have become popular, with good psychometrics. When selecting a scale it is important to attend to its original intended use and the wording in the items. Some may be more appropriate for clinical populations than general or occupational populations. Factors analyses carried out during the development of several of the scales show that fatigue is experienced along several dimensions, which can be summarized as general fatigue, physical fatigue, cognitive fatigue, emotional fatigue, and sleepiness. Debate as to whether fatigue is multidimensional are probably due to the fact that the latter four subscales tend to map on to an overarching scale of general fatigue. Accepting sub-dimensions of the experience of fatigue, we may need to reassess claims that subjective fatigue is poorly related to performance. Use of a fatigue subscale that is specifically related to the performance task of interest may result in closer correlation between subjective and objective fatigue, as has been demonstrated during the development of the SOFI scale. Likewise, little correlation between subjectively experienced fatigue and physiological measures, may be due to lack of specific matching of subscales and types of physiological measure. For example, measurement of physical fatigue may correlate better with task-specific measures of physical load than would general fatigue.

Subjective scales for sleepiness are well-developed and validated against certain aspects of performance e.g. time of day. Both sleepiness and fatigue measures can be usefully complemented by collection sleep diary data on sleep history and quality and other work-related activities.

The SOFI is a well-developed and promising tool for the assessment of fatigue in occupational groups. The profile of subscale scores appear to be indicative of the nature of fatigue in specific occupational groups. An interesting question is whether human transport operators in different sectors have similar or different SOFI profiles.

Although less studied, alertness may also be an important risk indicator for human transport operators, i.e. there may be many times when they do not feel alert, but where they do not feel fatigued. Evidence supports that alertness is a different state from wakefulness.

Fatigue that is specifically task-related may be experienced along dimensions that are different from fatigue that is due to general tiredness and work. Thus an important question for the study of human transport operators is whether there is a main task that may induce particular engagement and distress profiles that would best characterize the experience of fatigue when performing that task. This may be particularly relevant for the performance of high-stake tasks where effort cannot be reduced and it is important to maintain task performance.

Subjective reports can also be collected to assess fatigue effects on performance and other job-related activities. The more specifically the reports relate to the job being performed, the better. Self-reports can also be collected on compensatory strategies, health and latent performance decrements, in order to help understand fatigue and its effects, especially where objective measurement is not feasible. Comparisons of subjective and objective measures may also be very informative in terms of understanding fatigue.

Objective measures can be used to tap into physiological indicators of fatigue, sleep behaviour and performance. Of these, PERCLOS measures, actigraphy and PVTs may be most practically useful when data-gathering in the field. Measures of performance should be specifically matched to safety-related functions of interest.

Thus, despite the array of explicit and implicit fatigue outcomes considered, no measure is available that varies exclusively with fatigue. Indeed the absence of an objective and reliable index of fatigue is one reason why managers have not appeared to grasp that fatigue is a serious problem for transport operators (Dawson et al., 1998). To understand the effects of fatigue requires therefore that several measures are employed together. These measures can be collected at both individual and organisational level, and where possible be related to measures of fatigue causes or fatigue risk.

7 Effects of fatigue on performance and accidents

The effects of two main aspects of fatigue have been studied and are reported here: (i) acute total sleep deprivation, and (ii) sustained task performance.

7.1 Effects of sleep deprivation

7.1.1 Effects on performance

Effects on cognitive functioning

The effects of sleep loss on metabolic activity within the prefrontal and parietal cortices have consequences for a wide range of cognitive functions, mainly via effects on the prefrontal cortex (Kilgore, 2012). These include the following (Kilgore, 2012; Curcio et al., 2001; Dawson, 2011; Lim & Dinges, 2010):

- Alertness
- Perceptual skills
- Emotional processing and control
- Verbal fluency
- Reaction times
- Psychomotor coordination
- Response omissions
- Response inhibition
- Innovative and flexible thinking
- Judgments, decision making and risk assessment / attitude to risk taking
- Social cognition and moral judgment
- General cognitive slowing
- Memory deficits
- Effects on balance

These functions vary in their sensitivity to fatigue and their importance to the safety-related function of interest. It is also important to understand nuances in the findings. For instance, although memory lapses have been found to cause crashes, the precise effects of fatigue on memory are still not clear (Williamson et al., 2011). Some recent studies show difficulty in withholding responses with increased time awake (response inhibition), implying supervisory control decrements, but tests with more complex tasks indicate that development of optimal strategies for responding may be more of a problem than response inhibition.

However, the evidence that lapses and increased reaction times are linked to sleep deprivation is strong. The effects of sleep deprivation on specific cognitive and psychomotor functions have also been reviewed by Williamson et al. (2011), who report that simple reaction time, or variation in reaction time, is reported as the most sensitive measure of sleep loss, as most often found using PVT (Dinges & Powell, 1985). More recent research shows that sleep loss affects in addition to the above functions, complex cognitive tasks, such as verbal learning, serial subtraction and divided attention (Williamson et al., 2011).

Implications for performance

Concerning the implications of cognitive functional deficits for general performance, Dinges and Kribbs (1991) find that homeostatic sleep effects on performance from laboratory studies could be summarized as (Dinges & Kribbs, 1991):

- Increased variability in performance
- Accelerated vigilance decrement
- Decrements in both short term and longer term tasks, especially for vigilance tasks

Slowed response on simple reaction tasks has also been found in real world driving in response to acute sleep deprivation (Falleti et al., 2003). An important effect on driving of sleep loss is so-called wake state instability, which describes the "tug-of-war" effect of sleep loss on driving performance, caused by pulls between motivation to stay awake and sleep drives (Doran et al., 2001). The result is that normal performance at one moment may be followed by severe decrements in performance the next. Williamson et al (2011) add that sleep loss effects tend to be larger for monotonous or unstimulating tasks, or tasks involving passive concentration or difficult visual discrimination. While the evidence is less clear on complex tasks, there is some evidence that task complexity and familiarity may interact in determining which functions are most at risk.

Sleep restriction (to 2 h the night before) has been found to lead to a substantial (8-fold) increase in inappropriate line-crossings detected by a video camera in real road driving, compared to a non-restricted sleep drivers (Philip et al., 2005). In this study, the KSS score before the driving session, which was carried out at various times of day, corresponded well to performance. There was also an interaction between sleep condition and time of day. Sleep deprivation induced by 24 h of wake can produce impairments in dealing with unexpected challenging situations involving uncertainty, change and capacity to evaluate risks (Horne, 2012). People will be more susceptible to distraction. Horne (2012) reviews evidence concluding that these effects are not just due to sleepiness, but due to fatigued functions, particularly supervisory executive functions of the prefrontal cortex, which appears especially susceptible to prolonged wakefulness. Such deprivation may occur at the end of a first 12 h night shift, for example, and may leave workers particularly prone to unforeseen crises where staff may be inclined to resort to more routine, albeit highly trained but potentially inappropriate procedures, and then persevere unduly with such actions.

Reviews show that time-of-day effects on performance depend on the function being measured, and that they interact with homeostatic effects. Interestingly, the influence of hours since waking on performance seems to be at least as strong as circadian effects (Williamson et al., 2011).

Limitations of findings on sleep deprivation effects on performance

Much of the work summarized above, while valid, arises from laboratory or simulator studies which cannot approximate real world situations in which problems caused by decrements to functioning caused by fatigue may come to the fore when human transport operators must deal with unexpected or demanding situations rapidly in real time. Importantly, while it is known that chronic partial sleep deprivation influences attention and especially vigilance, its effects on other cognitive performance is not well studied (Alhola & Polo-Kantola, 2007). This is important given that human transport operators working shifts would be expected to be most affected by chronic partial sleep deprivation. The effects of the latter may be subtle but no less important. For instance, in terms of human transport operator safety there may long-term impacts on decision making.

Coping with sleep deprivation depends on several factors, especially aging and gender. Also inter-individual differences in responses are substantial. In addition to coping with sleep deprivation, recovering from it also deserves attention. Cognitive recovery processes, although insufficiently studied, seem to be more demanding in partial sleep restriction than in total sleep deprivation. Finally, motivation is often not considered in experimental tests of the effects of sleep deprivation on cognitive performance. When it is considered, it seems to have an effect (Alhola & Polo-Kantola, 2007).

7.1.2 Effect on accidents

As far as effects on accidents goes, proving a relationship is hard since it is difficult to prove that either fatigue or sleepiness was the cause, i.e. there is no after-the-event measure. This situation is made worse by poor operationalization of fatigue and lack of agreement on operationalization.

Nevertheless, there is good evidence that sleepiness leads to accidents. Having less than 9 to 12 hours sleep in the past 48 hours, and less than 5 hours in last 24 hours, appear to be threshold limits for crash causation in non-professional drivers (Connor et al., 2001). As far as commercial drivers go, drivers in fatigue-related crashes were found to have an average of 5.5 hours in the last 24 hours, compared with 8 hours for drivers in other crashes (Young & Hashemi, 1996). A threshold less than 6 hours of sleep in past 24 hours was found by others to be important in commercial drivers in road crashes or incidents (Hanowski et al., 2007). Sleep disorders are also robustly related to crashes involving fatigue (according to accident analyses), confirming sleep homeostatic effects (Williamson et al., 2011).

Studies of the effects of circadian lows are confounded by other factors. For instance it is difficult to compare those working through the circadian low at night to those working during the day, because nightshifts vary from day shifts in many ways that may affect fatigue (Folkard & Åkerstedt, 2004). Folkard (2006) elaborates on the factors that confound how other aspects of fatigue effects other than circadian drive timing of the accident peaks (Folkard et al., 2006). Most notably:

- time since waking
- time since starting work
- timing of rest breaks
- work quotas resulting in less work (and therefore less fatiguing tasks) being performed in the later hours at work
- occupational differences
- differences in the precise nature of the job being performed
- differences in lighting conditions

There does appear to be an increase in risk associated with an increasing number of consecutive night shifts that sleep models fail to account for. There also appears to be an increase in risk from morning to afternoon, and from afternoon to night, although this is somewhat confounded by time since waking (i.e. homeostatic drive) (Williamson et al., 2011).

Sleep problems have been found to increase work injuries by over 60 per cent, and 13 per cent of work injuries can be attributed to sleep problems (Uehli et al., 2013). There is also accumulating evidence that poor sleep quality and quantity, daytime sleepiness and sleep medication also increase work injury risk. Little is known about the mechanism by which sleep problems cause more injuries at work.

Again chronic partial sleep deprivation is not considered, even though this may have important effects on the performance of in human transport operators.

7.2 Effects of task/job-related fatigue

7.2.1 Effects on performance

Although it is difficult to separate the effects of task-related fatigue and sleepiness on performance outcomes, fatigued individuals have been described as exhibiting lapses in attention, longer response times and more frequent errors, and have increased difficulty identifying and processing salient information from the environment (Dinges & Kribbs, 1991; Harrison & Horne, 2000). Research has also indicated that sleep loss and fatigue can result in higher order cognitive deficits such as non-verbal planning and memory.

According to Krueger (1989), the continuous use of a specific cognitive function for a long time produces predictable performance decrements, which will be exacerbated by circadian nadirs, sleep drives, and workload (Krueger, 1989). Among the most well-known decrements are to those functions involved in vigilance. Indeed sustained attention has been given the most rigorous treatment in laboratory studies. There can be substantial performance decrements even for short-duration work requiring sustained attention (Temple et al., 2000). This so-called vigilance decrement has been observed in a range of occupational tasks involving monitoring and surveillance, including driving. Driving on real roads in Sweden between 01:00 and 03:00 shows a time-on-task effect, i.e. KSS ratings and lane crossings increased, and speed decreased towards the end of the night drive (Sandberg et al., 2011).

Task characteristics associated with cognitive fatigue are (Ackerman, 2011; Ackerman et al., 2012):

- Time on task. Task performance for periods lasting only a few minutes up to several weeks of an 8 h day have been studied. Many studies show minimal performance decrements for up to several hours of time on task, but the monotonous nature of the task needs to be accounted for.
- Task complexity. These tasks are most associated with specific cognitive fatigue decrements. The effects of performing simple tasks (e.g. reading, simple addition) over several hours are minimal; but more complex tasks (e.g. multiplication sums) lead to linear worsening in time taken to do sums when performed over several hours.
- Task engagement: "for a task that is very boring, repetitive…the onset of fatigue through time on task is very quick" (Hancock et al., 2012).

- Continuous versus intermittent work. Continuous work more likely to lead to performance decrements. Fatigue is especially implicated where there is press of continuous work and the work must be exact in terms of attention to detail, output precision, high cost of distractions; and where there is time pressure i.e. stimulus presentation rate not under control of operator e.g. display monitoring tasks (Ackerman, 2011).
- High stake tasks, tasks with high failure rates, tasks that are not intrinsically enjoyable (e.g. work versus leisure task) and information feedback are also implicated in decrement in cognitive performance. None of these factors have been studied in isolation or factorially combined.

There is agreement from non-driving tasks (Peiris et al., 2006) and driving simulator studies that time on task itself produces fatigue-related performance decrements (Oron-Gilad & Ronen, 2007), especially for monotonous drives on long straight roads (Matthews & Desmond, 2002; Saxby et al., 2013). The duration of real-world driving before testing has been found to be a major determinant of performance decrement in a driving simulator (Philip et al., 2003). Specific performance decrements have been reported as less efficient vehicle control, inefficient changing of gears, poor lateral control, late braking, failure to maintain constant speed (Craig et al., 2011). It is not clear how much of these performance effects are due to sleepiness, as these effects are pronounced late at night, and after extended periods on a long straight freeway.

Performance of simple or well-learned tasks, which can be executed in a more or less automatic way, can be upheld over long periods of time, after sleep deprivation or after prolonged performance of a demanding task. Complex tasks requiring deliberate control of behaviour (e.g. new or unfamiliar tasks) are more difficult to perform (van der Linden et al., 2003), or are poorly organized. This is due to decrement in the ability to regulate perceptual and motor processes in order to respond in an adaptive way to novel or changing task demands, also known as executive control. Thus after performing cognitive demanding tasks in laboratory, fatigued participants showed less cognitive flexibility and prolonged planning time, but there is no effect after performing a simple memory task (van der Linden et al., 2003). Some authors conceptualise executive control as important for the level to which actions can be selected based on goals and goal-related information. In fatigue it is not the goal or goal-related information that suffers, but the activation level through which a goal can influence the selection of actions.

Both complex tasks and boring, repetitive tasks may be fatiguing because of the level of attentional resources that they demand (Hancock et al., 2012). It is important not to confuse task complexity with task engagement. Tasks that are most vulnerable to fatigue effects appear to be monotonous tasks, especially those where there are several, competing demands (Matthews et al., 2010). Conversely, tasks perceived as engaging can be highly resistant (Holding, 1983). However, complex tasks may not necessarily be engaging.

Task demands, in particular working memory load, are significant in determining performance trends in response to circadian rhythms (Folkard & Monk, 1985). Task-induced fatigue, as opposed to sleepiness, has been especially associated with loss of motivation, mind-wandering, emotional distress, and various forms of physical discomfort (Matthews et al., 2012). There will often be attempts at coping, as drivers attempt to regulate their mental state out of safety concerns and need to maintain personal comfort. Common dimensions of experienced task-induced fatigue are given as task engagement (energy, motivation, engagement) and distress (tension, unpleasant mood, low confidence), and to a lesser extent worry (self-focused attention, low self-esteem, intrusive thoughts).

Effects of fatigue on latent performance

According to the CCM there will be four types of latent decrement to performance (Hockey, 1997): subsidiary task failure (selective impairment of low priority task components, neglect of subsidiary activities, attentional narrowing), strategic adjustment (within-task shift to simpler strategies, less use of working memory, greater use of closed-loop control), compensatory costs (strain of active control during performance maintenance, with increased mental effort and sympathetic dominance) and fatigue after-effects (post task preference for low-effort strategies, subjective fatigue and risky decision-making). Evidence comes from field experiments, including reduced subjective effort and less suppression of heart rate variability by driving examiners following more demanding work days (Holding, 1983; Meijman et al., 1992).

Limitations of findings on task fatigue effects on performance

There is overall lack of agreement about the strength of fatigue effects on task performance, how long a rested person can safely operate, and how much time-on-task research is relevant for the performance of real world tasks. Much of the evidence is derived from laboratories or simulators, but these situations are not as stimulating as real world, and do not have the same consequences. Respondents will therefore be less inclined to compensate to maintain performance. Perhaps the most enduring finding of performance-related fatigue studies is the stability of primary task performance under stress and high demands, with some studies showing that there are no effects on performance (Holding, 1983). Again this appears to be more so for naturalistic than laboratory studies, perhaps because the motivation for control is greater in the former (Hockey, 1997). In the real world there is also a need to consider how other aspects of the job interact with specific tasks to influence fatigue. For instance, one study estimates that almost one in ten of all types of work injury can be attributed to the elevated risk of work injury in evening or night schedules, but that risk arises from a combination of worker fatigue and lower levels of supervision and coworker support (Mustard et al., 2012). This highlights the importance of considering how other job characteristics interact with worker fatigue to influence performance.

It is nevertheless also important that latent effects on performance may often go undetected, both in the real world and in experimental studies. There may be effects on secondary aspects such as increased response variation, rather than speed or size of response; or other job-related tasks may be sacrificed in order to conserve performance of a primary task.

7.2.2 Effects on accidents

As a minimum, one must account for how the following combine in order to understand the effects of fatigue on accident risks: chronic partial sleep deprivation, time since waking (acute total sleep deprivation), time on task, time at work and circadian influences. This is complicated by the fact that it is often difficult to separate job and task effects from the effects of sleepiness drives.

A systematic review of high quality controlled studies finds that work periods longer than 8 hours a day carry an increased rate of accidents that accumulates so that the increased risk around 12 hours is twice that at 8 hours (Wagstaff & Lie, 2011). However, other evidence is less clear as to how time-on-task or time at work relate to safety outcomes, either in transport or other sectors. Part of the problem is in teasing apart sleep homeostasis and circadian effects. In driving there is also the confounding effects from higher traffic densities in rush hours and during day (Hanowski et al., 2009). However, several quality controlled studies across different occupations show that accidents, injuries and critical incidents in road transport increase from the second to fifth hour, proposed to be due inefficiencies in processing or lack of compensatory behaviour in the time before a rest (Williamson et al., 2011). Generally, as far as all occupations go, injuries and accidents risk are higher in the first half of the work day (note that this is for those working normal days, i.e. not a comparison of morning and afternoon shifts), and there are also reports of an increase in risk shortly following rest breaks (Tucker et al., 2006). This indicates that other factors are more important for accident causation than time on task, but there is a lot of variation and we can expect that time-on-task effects to be stronger for certain types of occupational tasks, like driving.

The effects of components of fatigue - sleep homeostasis, circadian influences and task effects – on performance, injuries and accidents was reviewed with the following conclusions (Williamson et al., 2011):

- There is clear evidence for the influence of sleep homeostatic effects on performance and accidents.
- Significant performance decrements are produced by task-related effects.
- The effects of task-related fatigue on accidents and injuries is unresolved due to lack of unsuitable studies.
- There is no direct link between circadian lows and performance or safety outcomes, probably because a combination of time-on-task and circadian influences is most influential.

Analysing data from naturalistic driving, it has been found that risks of any type of critical incident (defined by changes in acceleration measured by on-board instruments) increase in the first hour of driving, but then there is no increase after this, up to 11 hours of driving (Hanowski et al., 2009). Despite the many advantages of naturalistic observations, however, it is not always easy to control for traffic densities. While Hanowski et al. (2009) report that risk increases and decreases in line with traffic density, we might expect more fatigue-related incidents under monotonous conditions where density is low. This tendency for studies analyzing fatigue to report *all types* of incident or accident according to time of day or time on task is understandable, given the difficulties of attributing fatigue as a cause, but it makes interpretation problematic. What we need to know is whether there are increased risks of a *fatigue-related* accident at certain times of day.

7.3 Summary

Sleep deprivation has been found to affect a range of cognitive functions, most notably reaction time and lapses. Slowed and more variable reaction times are found in computer tests and real world driving. Functions affected by sleep deprivation that may be particularly relevant to human transport operators are reaction time, alertness, perceptual skills, decision making, judgments and cognitive slowing. Increased attention deficits and accelerated vigilance decrements may be particularly important.

The implications of these functional decrements caused by sleep deprivation for performance will depend on the task or job activities in question. Monotonous, unstimulating tasks are more likely to make performance vulnerable to functional decrements. Time of day will also influence the extent of functional decrements and related performance outcomes.

Importantly, sleep deprivation may produce impairments that reduces the ability of operators to handle unexpected, challenging situations, and make them more likely to rely on ingrained and inappropriate schemas. Sleep deprived workers may be more susceptible to distractions.

Many studies of the effects of sleep deprivation on performance are carried out on participants who are subject to acute total sleep deprivation. Many human transport operators will suffer from curtailed sleep over the longer term (chronic partial sleep deprivation). Little is known about how the latter affects performance, but we know that there are strong effects on attention and vigilance. In addition, studies of the effects of sleep deprivation on performance often use participants who may be less motivated to perform than people in real work situations. Thus human transport operators may demonstrate more compensatory effort in the face of sleep deprivation, and the effects on performance may be delayed. Nevertheless we can say that links have been established between sleep deprivation and accidents, strongly implying the involvement of sleepiness.

Isolating the effects of task- or job-related fatigue on performance from the effects of homeostatic and circadian influences is often difficult and rarely achieved. However, there is good evidence that sustained task performance results in decrements to sustained attention and functions involved in vigilance, especially where the task is continuous, perceived as boring, is demanding or taxes attentional resources. In terms of real world settings, the following may therefore result in task-related fatigue effects on performance involving human transport operators: driving on unstimulating, long straight roads; sailing a quiet ship on uneventful, open seas while following the same course; long straight, unstimulating rail stretches. These effects will of course be exacerbated by exertion to stay awake through circadian lows and sleep deprivation.

The job of human transport operator may also involve physically or other mentally demanding tasks that exacerbate vigilance performance decrements. Costs of attempting to maintain main task performance, include attentional narrowing, less use of memory, strain and effort, post-task preference for low effort, subjective fatigue and risky decision making. Thus the effects of fatigue on performance of the whole job may be important, as are interactions of other job characteristics, such as supervision levels, on performance.

The precise effect of task-related fatigue on accidents and injuries is unresolved due to lack of suitable studies, but people appear to be able to drive for long periods (up to 11 hours) without increased risk of an accident.

8 Safety relevant functions of human transport operators and links to fatigue

This section looks at the tasks and job contexts of human transport operators in the rail, road and sea sectors. The ultimate aim is to identify particular safety relevant functions that are likely to be influenced by fatigue. To inform this, we consider the jobs and tasks of human transport operators, according to the sector in which they work: rail (locomotive engineers), road (professional drivers) or sea (watchkeepers). We consider for each role the job context, working hours and shifts, safety behaviour and safety challenges, and possible links between fatigue and safety behaviours.

We begin by looking at how cognitive tasks of any human transport operator can be classified to help structure our thinking about different types of fatigue-related error.

8.1 Human error in task performance

Cognitive processes involved in task performance by the human transport operator are controlled at three levels (Rasmussen, 1986):

- Knowledge-based. Aspects of the task that are unfamiliar and rarely encountered will require effort and conscious attention
- Rule-based. Aspects of the task that require identification and recall of the appropriate response stored in the memory.
- Skill-based. Aspects of that task that are very familiar and routine, carried out automatically.

An experienced human transport operator may operate mostly at the skill-based level, but will still experience unfamiliar or deviant situations in daily work that involve rule-based and knowledge-based processing. Research evidence on cognitive control shows that different kinds of error occur at each of these three levels (Reason, 1990).

- Slips can be considered actions not carried out as intended e.g. misdialing a number, mistiming of action, pressing the accelerator instead of the brake. They occur at the skill-based level, and are more likely in situations that divert or tap the attention that in normal circumstances would be used to check skill-based processing against emerging events.
- Lapses are missed or disordered actions, e.g. when an operator fails to act according to procedure, misses a step in a procedure, or carries out a procedure in the wrong order, because he or she has forgotten or is inattentive or distracted, e.g. failing to check a signal on leaving the station. Lapses also occur at the skill-based level.
- Mistakes occur at rule-based and knowledge-based levels, e.g. thinking the speed limit is 40 km/h when it is 30 km/h.

To these we may add violations, where an operator will knowingly perform an incorrect action, perhaps as a valid attempt to cope e.g. a driver may decide to send an important text while driving in order to remove the distraction.

This way of thinking about human error in task performance is usefully supplemented by schema theory. According to schema theory, action is directed by schemas (Neisser, 1976). More specifically, our mental models of how the world works (schemas) leads us to expect certain cues, which in turn directs us to seek out certain kinds of information and provide a ready means of interpretation. As we act in our environment and sample information from it, our internal schemas are updated, and used to direct further searches and so on. Selection of the wrong schema can result in inappropriate action and performance errors (Norman, 1981). Of particular interest to human transport operator are mode errors, in which the system state is understood wrongly by the operator (Stanton & Salmon, 2009). In mode errors, intentions based on misinterpretation of the situation leads to employment of faulty schemas.

In the last few decades human error has been seen increasingly as a systems phenomenon, where salient human error is seen as caused by latent conditions in the immediate or removed system in which the human transport operator works. An example of an immediate system is the driver cabin or ship bridge design/conditions, while the removed system is typified by organisational safety culture or sectoral conditions. To avoid future accidents we should consider what is built into these systems that can distract the operator and leads to slips, lapses or mistakes, and what is it that increases the chance of mode errors.

Of particular interest to us is how fatigue influences different types of error. Are there certain types of task that, although important for safety, will be more vulnerable to fatigue and should therefore be in focus in fatigue studies? To help consider this we review below tasks carried out by human transport operators that are important for safety. By giving a systems context to these tasks we hope to consider how different factors in the system may lead to fatigue in different situations and make certain errors more likely.

8.2 Rail operators

Rail transport involves either cargo or passenger transport. Cargo transport occurs more often at night. It involves more shunting operations in station areas, which though they occur at relatively low speed, often occur without automated braking systems and involve crossing other tracks. Cargo trains may tend to travel longer distances with fewer stops. Passenger transport by train, especially local transport, is characterized by more time pressure due to more frequently scheduled stops. In both forms of rail transport, the locomotive engineer will be subject to extreme routine, periods of high demands, and a driving task characterized by vigilance.

8.2.1 Job context

The locomotive engineer's main task is considered to be a classic vigilance task. On long stretches of track when the conditions are good, there may be long spells of low arousal and monotony, and underload may become a problem (Dorrian et al., 2006). However, the task set is often a lot more complex (McLeod et al., 2005). In addition to operating the train, the human transport operator must anticipate, observe, interpret and react to signals, speed limits and other messages in the track and cabin environment, and act as a link between different actors in the system, such as the train controller, conductors, maintenance staff and passengers (Karvonen et al., 2011). The immediate system is not always optimal. For instance, in-cabin signals do not always correspond to track signal aspects, and the time period over which in-cabin signals apply range from a few seconds to several minutes. The driver must therefore interpret the meaning of the in-cabin signal by considering their track environment, which in some cases can be complicated. There may be many simultaneous demands. They may be concerned about punctuality, delays, engine overuse on slippery tracks, safe passenger embarkation, visualizing the aspects of dirty signals, finding signals in unusual positions, incoming telephone calls from train managers, communication with the conductor or other drivers in the cabin, or adverse weather such as low sun, fog or heavy rain (Phillips & Sagberg, 2010b).

Thus though it can be monotonous on certain stretches, train driving is often a complex task, involving multitasking and higher-level thinking. It often requires continuous constant alertness (vigilance) and continual object detection and recognition, recall, planning, decision-making and workload management (Dorrian et al., 2006). The stakes are high, given the number of passengers or nature of cargo on board, and given the potential for a catastrophic accident. Demands can also be high, for instance when punctuality is valued and there are delays in busy periods, or when the signal environment is taxing (Phillips & Sagberg, 2010b).

Route knowledge is a particularly important influence on train driving, allowing drivers to think ahead, control allocation of cognitive and perceptual resources based on expectations about the future, helping them to spot cues and interpret information. Lack of route knowledge can lead to errors by inexperienced drivers (e.g. not slowing down to see a particular signal facing a low sun early on a sunny day), whereas experienced drivers may rely on it too much, especially if they have been exposed to non-variant conditions for a certain stretch of track (e.g. believing a signal will show “go” because it always does at this time of day in this location). Route knowledge may become particularly influential when the situation is demanding.

8.2.2 Safety behaviour and safety-related challenges

There are two main safety aims for everyone involved in rail operations:

1. Keeping trains apart, with a focus on signals passed at danger (SPADs) as a cause of accidents;
2. Keeping a train from derailing, with a focus on speed around corners and at points.

Most trains now contain automated systems to assist the driver achieve these safety outcomes. In most cases these require that the driver acknowledge visual warnings (by pressing a flashing button) related to signal aspects and speed limits for the emerging stretch of track. If the visual warning is ignored, it is typically accompanied by an audible warning (intermittent beep or buzz). If this is ignored, automatic brakes are applied, but the driver can override these brakes.

Alongside operational and environmental factors, ergonomic factors have been found to be strongly associated with signal incidents (RSSB, 2004). Misjudgment of braking distances, unintentional speeding, missed or misunderstood signal aspects, fatigue, distraction and problems of sustained attention have each been suggested as influential (Andersen, 1999; Edkins & Pollock, 1997; Naweed, 2013; Pasquini et al., 2004; Dorrian et al., 2007). Distraction leading to inattention is more likely in stations, or if there are novel events, time pressure or poor driver-controller interactions (Naweed, 2013). One study of signal vigilance errors find that sustained attention is particularly influenced by distraction (Haga, 1984). An analysis of 96 accidents and incidents involving Australian train drivers between 1999 and 2008, confirmed that task demand factors, such as high workload, distractions and time pressure, were highly associated with the share of precipitative skill-based errors (Read et al., 2012). Knowledge factors (e.g. correct loading procedure) were highly associated with those incidents or accidents caused by mistakes (e.g. wrong loading method chosen by maintenance personnel).

Largely due to the periodic complexity of the job, it is not uncommon for drivers to respond to visual and audible in-cabin warning signals and still fail to apply the brakes – much to the astonishment of those who designed the systems (Hall, 1999). This implies the status of the system is misunderstood (mode error).

According to McLeod (2005), several factors influence a train driver's current understanding of the world in relation to automated alarms and warnings.

- Nature of alarm
- Signal visibility
- Magnets on the track ahead
- Driver interpretation of preceding alarm
- Expectations about current location
- Train speed to be achieved, by when and where it is to be achieved.

In our own research we have also found that some train drivers may use in-cabin alarms that warn about speed in relation to oncoming signals in much the same way as a car driver uses a speedometer, i.e. so that they can maintain speed at the speed of the speed limit (Phillips & Sagberg, 2014). This implies that drivers who get into the habit of driving slightly above or below the speed limit may become complacent on hearing visual and auditory warnings, and that this may increase the chance of a SPAD.

Analysis of hazardous signal approach events involving train drivers using a method based on this model (CREAM), showed the following (Phillips & Sagberg, 2014):

- Hazardous events were typically approaching at surplus speed due to late braking or no braking.
- In all cases this was because the driver had missed a trackside signal, in-cabin signal or both.
- Common reasons for missing signals were:
    - Deviant, unusual or demanding circumstances e.g. distracted by other task or searching for signal in deviant position.
    - Insufficient or forgotten knowledge about existing deviances or the possibility of deviances.
    - Overreliance on a mental schema for the emerging stretch of track, built up from high-frequency exposure to non-variant signal aspects for that stretch of track.

Others also report that the repetitive nature of train task (i.e. high-frequency exposure to non-variant signal aspects) is a problem that contributes a lot to skill-based and mode errors that are a common cause of incident and accident relating to both types of safety problem (i and ii above) (Edkins & Pollock, 1997). A common problem seems to be that circumstances involving distractions or demands force overreliance on those automated response modes that develop naturally through routine exposure to non-deviant situations (Phillips & Sagberg, 2014). Operating in the wrong mode for the situation leads to lack of awareness of the developing hazardous incident, which has been found to be important in rail crashes (McLeod et al., 2005). This is supported by an analysis of 19 investigation reports using two tools (HFACS and TRACEr) showed that the largest factor underlying driver error was incorrect driver expectations/assumptions about upcoming information (Baysari et al., 2009).

The repetitive nature of the task also contributes to periods of monotony, which have been found to result in alertness decline particularly when drivers are fatigued (Hildebrandt et al., 1974). Reports of a case series of train crashes and critical incident data suggest monotony is involved in crashes (Kogi & Ohta, 1975). However, monotony is not that well studied in rail personnel, although a recent experimental study suggests that the performance of simple repetitive tasks may be affected more than complex cognitions (Dunn & Williamson, 2012). Another study raises concern about the impact of automation (such as the European Rail Traffic Management System) on monotony, with initial experiments showing it causes time-on-task related vigilance decrement in simulated trains (Spring et al., 2012).

8.2.3 Working hours, shifts and schedules

Working hours for train drivers have generally decreased and rest times increased. However, shifts can occur at any time during a 24-hour period (i.e. through circadian troughs), vary from one day to the next, and be unpredictable. Crews can be on call waiting for work as well as having to stay overnight or travel to fetch a train. The result can be extremely irregular sleep patterns (Buck & Lamonde, 1993).

French locomotive engineers have been found to be sleep deprived especially before early morning shifts and after night shift (Cabon et al., 2012). Finnish engineers on irregular schedules, working nights and early mornings have increased sleepiness (Hämmä et al., 2002). In this case the 22:00-04:00 shift was associated with highest fatigue, and fatigue worsened over consecutive shifts. Coping measures such as napping, although feasible, are not used as often as they are in the air industry (Tirilly et al., 2011). A sample of Norwegian locomotive engineers also recognized schedule-related fatigue problems (Phillips & Sagberg, 2010b).

8.2.4 Links between fatigue and safety behaviours

Seventeen per cent of safety-related incidents on the railway have been related to fatigue (Kecklund et al., 1999).

Higher levels of fatigue and inattentiveness have been found to reflect circadian patterns for locomotive engineers. Unintentional sleep episodes are more likely to occur in early morning and mid-afternoon and temporal distribution of performance errors follow the same pattern (Mitler et al., 1988). This is backed up by studies showing that German drivers fail to respond to an intermittent vigilance device mostly around 03:00 h and at 15:00 h, although response omissions were also seen to increase with time on duty (Hildebrandt et al., 1974). However, *delays* in responding to vigilance devices are likely to occur between 07:00 h and 08:00 h, which probably relates to start of duty (Van der Flier & Schoonman, 1988). Partly in line with this, SPADs may be more common at the start and end of duties, especially if the duty begins early in the morning (van der Flier & Schoonman, 1988).

Case studies of drivers involved in accidents suggest that backward rotating shifts may be particularly problematic for safety performance, and several studies of drivers involved in critical incidents show a link to sickness absence or psychosomatic problems, which may or may not indicate fatigue (Fairbarn, 1959; and Davis, 1966, cited in Buck & Lamonde, 1993).

Despite these studies, Buck and Lamonde (1993) claimed there was insufficient evidence that critical incidents occur simply because drivers are fatigued: "Prolonged duties, and poor inadequate sleep and rest, cause drivers to be tired, but there is no evidence that they cause them for that reason to have critical incidents." The authors claimed that there was a need to study specifically the effects on safety of the combination of time of day and time-within-duty, rather than the effects of general fatigue (Buck & Lamonde, 1993). More recently, Williamson et al. (2011) claim that studies of fatigue in train drivers that involve safety outcomes are mostly case series and case reports, and generally lack information about recent sleep history and other causes of fatigue.

However, studies are beginning to address these problems. A separate analysis of 40 rail safety investigation reports using the Human Factors Analysis and Classification System (HFACS) showed that of those incidents that were due to unsafe acts, slips of attention (i.e. skill-based errors) associated with decreased alertness and fatigue were the most common (Baysari et al., 2009; Baysari et al., 2008). Inadequate system design was frequently identified as an organisational influence of attention failures.

A series of studies on fatigue in Australian drivers has been carried out by Dorrian and colleagues. Simulator studies showed that operator fatigue leads to inadequate planning for speed reduction, i.e. delayed braking or braking errors (Dorrian et al., 2006). Failures to act increased with fatigue (rated using single-item VAS) while incorrect actions decreased. The authors interpreted the latter as being due to cognitive disengagement from the simulated driving task (Dorrian et al., 2007). Self-reported alertness decreased and PVT reaction times increased also with increasing fatigue (Dorrian, Roach, et al., 2007). Drivers themselves were also moderately aware of the fatigue-related performance decrements.

In a subsequent study, fatigue in locomotive engineers was measured objectively based on predictions from driver work history (based on sleep model parameters using the Fatigue Audit Interdyne Software), along with driving performance using data loggers from 50 locomotives running between Adelaide and Melbourne (Dorrian et al., 2007). A link was found between fatigue and fuel use, heavy brake use and maximum speed violations. Heavy braking and speeding was shown to occur predominantly on flatter, and therefore more monotonous stretches of track. Drowsiness has also been linked to delayed, and therefore heavy braking in other studies (Kogi & Ohta, 1975).

Dorrian et al. (2007) conclude that fatigued driving is detrimental to the appropriateness of the driver's plan for the emerging stretch of track, and that operations may be more vulnerable to driver fatigue on certain stretches of track. This is important because it means that fatigue may exacerbate what is already a central threat to safe operations by locomotive engineers: employment of inappropriate schemas developed by routine exposure to non-varying situations. Support for this idea comes from brain imaging studies, which show that slow reaction times induced by sleep deprivation is associated with low cognitive engagement and operation of brain regions in default mode (Drummond et al., 2005).

8.3 Professional drivers on the road

There are many different types of occupational driver on the road, who are involved in the transport of passengers and goods. Our focus is on those who drive trucks or buses, i.e. those involved in transporting larger amounts of passengers and goods. An important difference, independent of what is being transported, is whether the operator is involved in short- or long-distance driving. Long-distance driving may involve long periods of monotony, and be carried out at all times of day. It may therefore tend to be more associated with sleepiness. There may be pressure from delivery deadlines, route timetables and queues on roads or for ferries along the way. There may also be physically demanding work in terms of loading, unloading, tyre changing, lorry maintenance, fitting equipment and so on. Short-distance driving may involve driving in complex traffic environments, intense stress and multiple, competing demands.

8.3.1 Job context

The tasks of a commercial human transport operator in the road sector can be categorized as driving and non-driving tasks. Naturalistic data from the US suggests drivers spend 66 per cent of shifts driving, 23 per cent working on other tasks, and 11 per cent resting (Soccolich et al., 2013).

Driving requires continuous attention to the traffic situation, such that any changes can be understood and reacted to. In cases where the route is well known, a driver may be able to focus on the traffic situation. However, if a driver needs to find his way, he will also need to read traffic signs, signals and directions. Demands can be intense, for instance in adverse weather with poor visibility, or in complex or unforeseen situations in fast moving traffic. On the other hand, the driver having driven long distances may be subject to underload and boredom. Drivers may have varying degrees of influence over their driving schedules, with many schedules being determined by logistics operators. Perishable loads and passengers will need to be delivered on time, whereas safe delivery of hazardous loads is prioritized. Some vehicles may cause severe vibrations which can be fatiguing, especially if they lead to musculoskeletal problems. The extent to which such factors contribute to driver fatigue has been somewhat overlooked (Phillips & Bjørnskau, 2013). Psychosocial factors may also induce fatigue in the long run, such as stress from standing in queues, restricted parking, driving in busy traffic or solitude from long hours away from home.

Non-driving tasks in road haulage have been classified as transport-related administrative activity (assignment order, delivery note), taking part in loading operations (cargo or passengers), and taking part in vehicle or load inspections (Wioland, 2013). Non-driving tasks may themselves cause or contribute to the fatigue that affects driving performance. For instance, physical fatigue may result from climbing into and out of the vehicle, dragging pallets over gravel, and from loading tasks, either directly or indirectly via musculoskeletal problems they may induce. Owner drivers are more likely to load/unload than company drivers (Feyer &

Williamson, 1995). Manual handling is a problem for human transport operators (Goode et al.). Finally, drivers may be involved in a lot of waiting around while they are not driving, e.g. sitting on ferries, waiting for goods to arrive or be off-loaded.

As much as 25 per cent of the work of long-haul truckers can involve other activities, such as waiting in queues or waiting for or carrying out loading activities, for which they may or may not be paid. In particular, drivers who wait in queues are found to experience fatigue more often than those whose work involves more driving (Williamson & Friswell, 2013). Worse still, drivers who were not paid to wait i.e. those who were paid per delivery rather than per hour, were found to drive longer hours, above the legal limit, and had the highest levels of fatigue. It is not known whether this fatigue affected safety-related behaviour or risk, but it demonstrates the importance of considering the whole context in which drivers operate.

8.3.2 Safety behaviour and safety-related challenges

The most common errors committed by drivers driving round an urban test route have been classified as violations (too fast), misjudgements (e.g. of gap when turning), perceptual failure (fail to observe pedestrian) or inattention (Young et al., 2013).

A generic road driver taxonomy has been presented with underlying psychological mechansims (Stanton & Salmon, 2009), drawing from previous work on human error in general and road driving behaviour. It identifies and exemplifies 26 different external error modes. The common underlying psychological mechanisms are classified as action execution (e.g. fail to check mirror, fail to brake sufficiently), perception (e.g. fail to see pedestrian), attention (e.g. fail to see car in front, but also includes distractions e.g. by phone), situation assessment (e.g. misread signs, misinterpret correctly read signs), and memory (e.g. forget to look behind before reversing).

Treat (1975) has classified those errors most commonly involved in road accidents. Recognition errors (e.g. inattention, distraction, look-but-failed to see) contributed to 56 per cent of crashes; decision errors (e.g. misjudgement, false assumption, improper manouevre) contributed to 52 per cent of crashes and performance errors (overcompensation, panic, freezing) to 11 per cent of crashes.

8.3.3 Working hours, shifts schedules

Long-haul drivers will often drive through the night for reasons of efficiency, either because the traffic is light or to exploit driving hours regulations to the full. Express bus drivers may also drive through the night and early hours. A lot of sleep will be done in sleeper berth or motels, sometimes in the day and sometime this sleep will be split (Feyer & Williamson, 1995).

Fatigue profiles of short haul light drivers have been compared with those of long distance heavy truck drivers in Australia (Friswell & Williamson, 2013). Most short haul drivers work five days a week whereas long haul drivers could work 4, 5, 6 or 7 days a week. Getting a sufficient sleep was a problem for 30 per cent of short haul drivers, but only 7 per cent of long haul drivers. Short haul drivers reported working long daytime hours with too few rest breaks and high exposure to intense urban traffic and uncomfortable driving position. Fatigue prone hours were between 14:00 and 17:00 h. Heavy drivers also reported long hours, but also at night, and highlighted dawn driving and time spent waiting to load and unload as particular fatigue contributors. Surprisingly, at least as many short haul as long haul drivers reported fatigue was a problem for them, although it was not perceived as a problem for the industry as a whole.

Interactive causes of fatigue have been well researched in road operations, especially that between time of day at which task is carried out and both sleep deficit and time-on-task (Brown, 1994). A recent study suggests that both a 28 hours sleep deprivation and time of day affect driving performance, but only in combination (Williamson & Friswell, 2009). Another study finds that truck drivers who begin shifts at midnight and end at 10:00 h, face an increase in crash risk after consecutive days of driving that is far greater than that seen in day drivers driving the same length of shift (quoted in (Hartley, 2007). A recent real-world driving study demonstrated a dose-response relationship between duration of driving and impairment from nocturnal driving (Sagaspe et al., 2009). It has also recently been pointed out that the evidence for a pure circadian effect is not straight forward, with most peaks in accident risk occurring earlier than circadian troughs, because studies have not adequately controlled for time-on-task effects (Williamson et al., 2010).

The effect of sleep deficit on fatigue outcomes is exacerbated if the time of day of recovery sleep is not optimal, and this interaction is important in chronic fatigue. One field study finds that many drivers were fatigued before a trip began because they did not recover from workload over the last week, in which night work, short bursts of sleep, and daytime sleep were particularly prevalent (Feyer & Williamson, 2000).

Finally, we should note that many bus drivers work split shifts in order to help bus companies cope with rush hour demands. Thus for example they might work one shift from 06:00 to 10:00, and another from 14:00 to 18:00 h. Split shifts are seen as problematic by drivers and researchers, in terms of fatigue and effects on work-life balance (Phillips & Bjørnskau, 2013).

8.3.4 Links between fatigue and safety behaviours

The occurrence of fatigue in commercial and non-commercial drivers is well-established (Phillips & Sagberg, 2010a). Its effects on performance have been witnessed first-hand in naturalistic observations (Hanowski et al., 2009). Sleep drives and task-induced fatigue associated with long, monotonous drives have been cited as the main causes (Matthews et al., 2012). Thus we can expect interactions from time-of-day and time-on-task and sleep history.

Williamson et al. (2011) argue that three types of evidence considered together give strong evidence for the link between fatigue-related performance and safety outcomes. These are:

1. Studies linking self-reported cognitive failures and accident outcomes.
2. Studies linking cognitive performance predictors with objective accident or injury rates.
3. Accident report analyses.

Type 1 studies suffer from subjective reporting inaccuracies and biases, but in any case demonstrate a relationship between reported accidents and reported cognitive failures. They also show that driver errors are associated with problems of attention regulation and inattention, which are consistent with fatigue. Type 2 studies are more reliable, since they involve taking objective measures of cognitive performance and accident rates, albeit one before the other. They also show links between poorer performance and crashes. Type 3 also implicate driver behaviour in road crashes.

Although it is difficult to attribute fatigue as a cause, the skill-based errors and lapses that typify driver error occurring immediately prior to crashes involving occupational fatalities could certainly be caused by fatigue effects on performance (Hobbs & Williamson, 2003). Fatigue was is not associated in incidents caused by violations, rule-based and knowledge-based errors, as might be expected.

Monotonous driving is often cited as an important factor in fatigue-related safety outcomes. Fatigue has been found to be a stronger factor in accidents on motorways than on other roads (Horne & Reyner, 1995). A real road study of monotonous driving was conducted that assessed vigilance objectively (EEG, auditory reaction time). Results showed that prolonged daytime driving under monotonous conditions leads to a fairly linear and continuous reduction in vigilance over four hours of driving (Schmidt et al., 2009). Interestingly, subjective assessment of vigilance decline, using KSS and others, was fairly consistent up until 3 hours. Monotony has been interpreted as unmasking problems caused by homeostatic and circadian sleep drives, making drivers less able to compensate (Caskadon & Dement, 1981). Other authors construe the problem as passive fatigue, characterized by boredom and underload (driving on long straight road, good driving conditions). Passive fatigue is thought to be more of a problem in terms of maintaining performance than active fatigue, which occurs when drivers must elicit frequent control responses in conditions of high workload (e.g. busy motorway, adverse driving conditions). Desmond and Matthews (2009) think that active fatigue would result in increased task-focused coping, while passive fatigue would result in avoidance coping and task withdrawal, i.e. there may be different subjective states and coping responses. This is supported by simulator studies in which active fatigue was characterized by increased distress while passive fatigue was characterized by reduced task engagement. Delayed braking and steering variability is higher in the passive fatigue mode. Worryingly, as they withdraw from the task, passively fatigued drivers may be more inclined to employ automation available to them, such as cruise control, which may thus increase task disengagement and hence the pace of fatigue (Matthews et al., 2012). This theory is consistent with a UK study, which found that sleep varies as a causal factor in accidents, from between 3 and 30 per cent, according to the type of road. Higher density traffic caused more sleep-related accidents in the city, but less sleep-related accidents on rural roads and motorways (Flatley et al., 2004).

For monotonous driving there is also evidence that:

- Steering wheel movements deteriorate faster (Thiffault & Bergeron, 2003)
- General effort increases (implied by heart rate measurements) (Pastor et al., 2006)
- Mirror use decreases in lined with decreases in alertness, although changes are slight and shown over only a short time (45 min) (Pastor et al., 2006)

Another problem for long, unstimulating drives is the so-called "Driving Without Awareness Mode" (DWAM) and the related phenomenon of highway hypnosis. In both conditions the driver has very low or subconscious awareness of his or her road environment, which has obvious implications for safety. However, most research on these conditions is only descriptive (Cerezuela et al., 2004; Sagberg, 2011).

Despite findings on the effects on performance of monotonous driving, Williamson et al. (2011) report that "we found no controlled studies documenting boredom and monotony as causal factors in fatigue crashes, either as independent risk factors or in combination with known causes of sleepiness". Thus we must be careful in interpreting findings on monotonous driving, as to distinguish sleep drive effects from task effects. One explanation for the lack of robust evidence may be that, as found for rail operators, driver distraction or deviant or demanding situations could increase the likelihood of driver errors (Young et al., 2013), and unmask the effects of the monotonous task on performance.

A recent naturalistic study of US truck driving included non-work activities as part of the analysis of the driver's working day (Soccolich et al., 2013). US law allows for 11 hours of driving in a working day, but 14 hours of total work. In this study safety-critical events (predominantly "crash-relevant conflicts" and "unintentional lane deviations") increased with time on task across driving hours, from 0 to 11 hours, independent of time of day. A break from driving was found to reduce risk for 1 hour following the break. However, safety critical event risk was also found to increase across all work hours. While there was no significant increase in safety critical events between the eighth and eleventh driving hours, safety critical events were found to increase for drivers who began their day with non-driving work and drove deep into the 14 hour work day.

Finally, it may be of note that according to self-reports, fatigue produces less effective negotiation in urban traffic among short haul drivers, but problems with vehicle control and monotonous driving for long-haulers (Friswell & Williamson, 2013).

8.4 Watchkeepers at sea

Shipping is unique in that all rest must be obtained in a workplace that may cross time zones and be subject to varying degrees of motion, temperature and noise, i.e. a fatiguing environment (Phillips, 2000). Like other freight transportation modes, merchant shipping involves long work weeks, nonstandard work days, extensive night operations, and alternating periods of intense effort and monotony. There is pressure to improve productivity in merchant shipping through reduced manning, reduced port turnaround times and decreased layovers (Wadsworth et al., 2008). For economic reasons and with introduction of new technology, ship manning levels have been reduced worldwide. As early as 1990, average US crew size has been reduced from 35 to 21 (Pollard et al., 1990). In 1980 a cargo ship would have been manned by between 40 and 50 crew, whereas it is now possible to manage the large ships with less than half this number (Hetherington et al., 2006).

Regulation can be complex, occurring at local, national and international levels. Recent regulatory improvements by International Maritime Organisation (IMO) include that a Safety Management System (SMS) be established i.e. safety culture should be established as a main defence against risks, rather than insisting on prescriptive inflexible rules (Chauvin et al., 2013). At the same time, the so-called Manila amendments to IMO's international convention on standards of training, certification and watchkeeping (STCW), which came into force in 2012, place Bridge Resource Management (BRM) into the mandatory section of the code. BRM is a system that ensures the proper allocation of all available resources on the bridge. It addresses training of non-technical skills (situation awareness, teamwork, leadership, communication) and their assessment, and in this way is analogous to crew resource management in aviation. BRM has been adopted by many shipping companies since the mid-90s and its recommendation in the International Safety Management code (Hetherington et al., 2006). However a recent analysis of collisions finds leadership non-compliance with SMS and BRM a problem, and the effectiveness of training courses in BRM is questioned (Chauvin et al., 2013).

8.4.1 Job context

Commercial ship crews typically comprise the master, a few deck officers, engineering crew and various ratings. The deck officers are responsible for watchkeeping, and comprise the master, and first, second and possible third mates (Phillips, 2000). (For more detail of tasks see "Working hours, shifts and schedules" below.) Task demands associated with cargo loading, navigating into ports, and attending to unanticipated repairs can lead to long periods of intense work that can interrupt and disrupt the routine sleep schedules. On the other hand bridge automation has increased the role of watchkeepers and bridge crew as system monitors subjected to long periods of intense underload. Individual roles may be particularly susceptible to fatigue. Phillips (2000) reports that ship masters rarely suffer from sleepiness, while second mates who work the 00:00-04:00 shift, and thus often work through circadian lows, do.

The situation on smaller vessels will necessarily be more flexible, with say a skipper and two deck hands, whose watchkeeping may depend on the particular activities of the boat, with sleep of the whole crew arranged around fishing activities, for instance.

In fact the nature of the watchkeeper job as a whole is determined in large part by ship activities of any ship (Starren et al., 2008). While watchkeeping and other bridge roles may dominate, bridge crew will also be involved in other ship activities, especially on less larger ships. An important influence on the extent of these activities is the nature and frequency of port calls. For instance, some ships will make several port calls in quick succession. This increases the number of intensity of tasks to be performed, and may lead to more fatigue (Pollard et al., 1990). To a certain extent this depends also on time pressure and nature of loading and unloading activities e.g. passengers versus hazardous loads. Reduced port turnaround times have led to less time for sleep after loading operations (Wadsworth et al., 2008).

Other ship-related determinants of the intensity of the job include whether operation is in open or congested waters, the length of the tour, weather and ship-design factors. The latter include:

- Level of automation, reduce workload but increase monotony
- Equipment reliability can influence workload
- Noise, vibration, temperature, ship motion = physical stress, sleep disturbance

Wadsworth et al (2008) report that factors specific to seafaring, such as environmental factors and switching to port work, are responsible for between 15 and 23 % of the variance in acute fatigue, while organisational schedules and psychosocial factors common to all workers are responsible for 18 to 20 % of the variance.

Crew fatigue is affected by three basic mechanisms: number of hours worked (see below), ability to get regular and uninterrupted sleep, and exposure to stressful mental or physical conditions (Wadsworth et al., 2008). Looking at organisational causes of these conditions, Akhtar finds manning levels are important (Akhtar & Utne, 2013). Pollard et al. (1990) claim that crew size can be reduced without impacting fatigue by;

- Controlling the number of hours required to complete the ship's mission
- scheduling work to reduce sleep disruption
- operations which limit adverse environmental, workload and other effects.

The ability to control these factors will however vary according to shipping operation and company.

Intoxication or its effects appear to be a particular problem at sea, presumably due to the effects of drug and alcohol use while on shore overlapping with ship duties. Almost a third of one large sample of Australian seafarers exceeded safe limits for alcohol consumption (Parker, 2002). Overlap may be more likely when the drugs are used to mitigate the effects of the job or treat chronic health problems (Pollard et al., 1990). Not only do they increase fatigue and affect the crew performance directly, by reducting alertness, judgement and coordination, they place extra load on the remaining crew. Ironically, intoxicants may be used to mitigate the effects of fatigue or fatigue-related stress (Pollard et al., 1990).

In a US study based on interviews with merchant vessel officers and crew surveys, (Pollard et al., 1990) found that organisational factors (i.e. how a ship is managed) was key in determining fatigue, through influencing:

- Crew continuity (crews with high continuity have lower fatigue than those with high turnover, presumably because it reduces workload by reducing the need for supervision and training)
- Work rules
- Pay system (crew can be more fatigued and perform inefficiently if it is incentivized to work a lot of overtime to maximize pay).
- Training
- Standardization
- Paperwork (perceived as a burden leading to officer fatigue, depending on the number and type of report required by managers of the operating company, the degree of automation of report generation and government requirements)
- Officers' people management skill and styles ie psychosocial work environment
- Inspection and maintenance policies – where high levels of maintenance required, crew must work more hours per mission and rest more likely to be disturbed

8.4.2 Safety behaviour and safety-related challenges

Periods of extremely low workload may be a problem in any situation where the primary task is to act as monitor over sustained periods, as it is when watchstanding at sea (Pollard et al., 1990). This is exacerbated when the system monitored is highly reliable and unchanging, intervention is rarely required, and there is little feedback when it is. Pollard et al. (1990) describe that simple inattention to proper external stimuli is a particular problem for watch crew. It is exacerbated by inadequate supervision making it easier to attend to distractions, introspection or concern about irrelevant tasks, and boredom and monotony.

While monitoring and vigilance tasks may dominate, they will often be interspersed with periods of intense mental workload, where crew members may have to make a variety of critical responses to different systems over a short time e.g. maneuvering in restricted space or emergency situations. Although there is less work in the literature, we may infer from road and rail studies that these periods will be associated with cognitive error in cases where crew are fatigued.

According to Perrow (1999), error-inducing characterstics are inherent in the global shipping system, including social organization of personnel onboard, economic pressure, structure of the industry, insurance and difficulties of international regulation. Certainly economic pressure has led to reduced manning, which is often cited as a safety challenge (Pollard et al., 1990). This is because it increases workload from more operational and administrative tasks, reduces monitoring of crew performance (making it more likely that errors are not caught in time), reduces the availability of social support on board (which has been associated with self-reported fatigue; Wadsworth et al., 2008), and reduces situational awareness (by automation of whole tasks). Staff must also cover for others when they are sick, fill-in when irregularities occur, and work more in off-periods to get the job done (Akhtar & Utne, 2013). There are related claims that over-reliance on automation may amplify the role of human error in accidents (Lützhoft & Dekker, 2002). For example, crew may search to confirm hypotheses formed by faulty equipment.

Many of the considerations for better integration of automation with crews outlined by Pollard et al (1990) 25 years ago do not appear to have been made. These include that the system provides status information about the ship's function to help bridge personnel maintain situation awareness and user confidence, provide systems information that enables the user to anticipate malfunctions and which is complementary to the existing organisational structure, and makes appropriate use of staff skills and expertise. The latter is important following claims that many automated systems demand a level of monitoring that is beyond the reach of most humans (Parasuraman, 1987). Moreover, situation awareness is reported as responsible for 71 per cent of all human error types on ships, according to international data (Hetherington et al., 2006).

Behaviourally-related causes of collisions are cited as poor lookout, poor use of radar, improper manning, poor employment of ratings on the bridge, lack of competency, poor teamwork on the bridge and poor communication between ships (Chauvin et al., 2013; MAIB, 2004). The complexity of manouvering ships away from each other, and the importance of effective communication and coordination during this phase is also highlighted (Perrow, 1999). A separate report, using an accident analysis method developed to account for maritime contextual factors, rather places the emphasis on decision making errors as direct contributors to collisions, with common precursors including loss of situation awareness, poor attention, and deficits in communications on the bridge (Celik & Cebi, 2009).

8.4.3 Working hours, shifts and schedules

On vessels of any size, the demands of time and tide put pressure on the ability of crew with limited manning to obtained regular and extended sleep. Watchkeepers in particular may suffer from fragmented sleep, even though they may need it the most in terms of safety. Unpredictable arrival and departure times makes for unpredictable and disrupted, non-routine sleep periods.

Typically, each officer takes responsibility for a 4 hour watch two times in any 24 hour period (e.g. 0400 – 0800 and 1600-2000) with an 8 hours "rest" period in between each watch (Raby & Lee, 2001). Thus the system can be described as 4-8-4-8. This is a three-watch system because three groups or "watches" are required to rotate in order to provide 24-hours of cover per day. Three-watch systems have the advantage that there is, at least in theory, more time off than on two-watch systems (e.g. 6-6-6-6), but they require lower levels of manning for the same number of crew, and low manning can itself lead to fatigue problems (Akhtar & Utne, 2014).

Even though officers have 8 hours free from watchstanding on a 4-8-4-8 system, they have other duties for which they are responsible. The first mate manages mooring operations and cargo handling, while the master is in charge overall, and specifically of crew safety, budget, information control and security. Beyond the watch schedule, watch officers often work overtime during their off-watch hours to complete repair, maintenance, and administrative tasks. The combination of watch standing and overtime work may result in more than 10 hours of work each day, with a 12 hour day being common (Raby & Lee, 2001), something which is not dissuaded by a culture of self-reliance and willingness to do all (van Leeuwen et al., 2011). Thus in reality a 4-8-4-8 work schedule effectively forces mariners to sleep in two periods of 2 to 6 hours continually, without any days off, for many weeks.

For many though the 6 hours on / 6 hours off or 6-6-6-6 two-watch system is seen as even worse, and recent studies show that subjective and objective sleepiness are higher, even though the effect on performance on reaction time tests remains unclear (Härmä et al., 2008; van Leeuwen et al., 2011). Other watch systems include the 8-4-4-8, 8-8-4-4 and the 12-12. According to Pollard et al. (1990) a three-watch schedule is common on voyages of over 600 miles and on larger ships, permitting an eight-hours rest period, assuming no port calls (e.g. 8-8-4-4 system), while 6-6-6-6 may be more common on smaller vessels. If there is no port layover, the 6-6-6-6 system does not allow for readjustment of circadian rhythms, and there may be similarities to the split shift problems of bus drivers, in that what is construed as a 12-hour day (two "on" shifts of 6 hours) is in effect an 18-hour day, because it not possible for crew to sleep in 6 hours in which they are "off" in the daytime (Wadsworth et al., 2008). Generally the 6-6-6-6 and 12-12 systems are deemed by safety experts to be least preferred (Akhtar & Utne, 2013), though crew may not concur for sociocultural reasons (Kongsvik & Størkersen, 2011). According to a recent UK survey, most engineers and deck crew work either 6 or 12 hours on (Wadsworth et al., 2008).

A recent attempt to introduce the three watch system over the 6-on-6-off on Norwegian supply ships showed that crew slept better, but there was no effect on fatigue according to self-reports, reaction time tests or physiological measures (Kongsvik & Størkersen, 2011; Olderkjær, 2011). One of these studies also reported that crews try 8-8-4-4 but revert back to the 6-6- system (Kongsvik & Størkersen, 2011).

Reduced manning has led to increase length of actual duty periods (particularly for those involved in loading operations), as confirmed by reports that most seafarers feel their hours have increased with effects for health and safety (McNamara et al., 2005).

8.4.4 Links between fatigue and safety behaviours

Studies of fatigue on board find that sleep is poorer and fatigue perceived as greater for the "near sea" sector (short sea and coastal shipping) than support shipping, with over half of respondents in the former sector saying there was no opportunity for them to have six hours of uninterrupted sleep (Smith et al., 2003). Within the sector ship type also played a role, with crew on ferries reporting more fatigue than crew on other vessels. Predictors of fatigue were identified as working hours, sleep problems, tour length (short tours worse), shift length, job demands, stress at work and standing watch (Smith et al., 2003). Furthermore, several risk factors present together appear to increase risk of fatigue in additive fashion (Wadsworth et al., 2008).

For watchkeepers, causal factors are found to interact in a complex fashion resulting in widely varying levels of fatigue according to ship and situation. For example, a demanding watch system may be exacerbated on ship missions with minimal manning where crew are required to work part of their off duty to make the ship function. The realities of life on board man ships will mean that it is not possible to keep to the IMO regulations of working no more than 12 hours without a 6 hour break. (Hetherington et al., 2006) claim that the chief officer must be present at all times during discharging operations which can take up to 44 h for large tankers. There are large differences in fatigue levels among ships and different phases of a voyage on the same ship.

So what is the evidence for links between fatigue, safety behaviour and accidents?

- The effects of fatigue on some crews are increased reaction time, reduced attention, diminished memory and mood changes (Pollard et al., 1990).
- A recent analysis of accident investigation reports of groundings using CREAM, reveals that irregular working hours, inadequate task allocation and high demands are common antecedents of fatigue-related groundings, and that fatigue is a factor in 41 per cent of groundings (Akhtar & Utne, 2014).
- There is evidence that fatigue leads to poor cognitive performance and other health problems among seafarers, especially when it lasts several days or more, and when there is work stress and poor sleep (Wadsworth et al., 2008).
- Physical fatigue from loading and other onboard demands is likely to increase attention to somatic problems, and reduce attentional processing capacity to external stimuli, miss critical signals. May also result in loss of coordination or response accuracy (Pollard et al., 1990).
- Extended hours on duty and hours worked in last three days are associated with fatigue-related marine accidents (Raby & Lee, 2001).
- Smith (2001 cited in Hetherington et al., 2006)) analysed MAIB accident data to conclude that fatigue-related accidents were more likely during the first week of a tour and the first four hours of a shift, between 09:00 and 16:00 and in calm waters. However others report that fatigue-related accidents follow circadian patterns, occurring in the early hours and afternoon (Raby & Lee, 2001).
- Actual sleeping leading to loss of situational awareness is a relatively common cause of accidents (Phillips, 2000).
- Some say groundings more likely to be sleep-related, but others say that collisions equally likely to be linked to fatigue (Phillips, 2000).

8.5 Summary

Human error is often classified as mistakes, slips, lapses or violations. Mistakes occur in those aspects of the task carried out at knowledge- or rule-based levels, whereas slips (unintended, mistimed or misdirected action) and lapses (omission, wrong procedural order) occur at the skill-based level. Errors at the skill-based level often occur due to distraction or attention problems. Most tasks carried out by the human transport operator with moderate experience occur at the skill-based level, and will involve schema employment.

The job of the locomotive engineer is highly skilled, highly routine, sometimes monotonous, but often demanding. There can be periods of fast-moving complexity requiring rapid decision making, and these are necessarily assisted by selection of a schema on which to base actions. On the other hand the high level of routine means there are sustained periods of monotony, especially on long unstimulating stretches of track, and this may lead to vigilance problems. The high level of routine also means that the same schema that are employed are reinforced time and time again. This is a problem in deviant situations on the rail, because selection of the "normal" schema in situations that are abnormal can lead to unsafe actions, and the driver is more likely to depend on routine schema when he or she is distracted, inattentive or fatigued.

International studies show that shift work patterns in locomotive engineers lead to fatigue and sleepiness. Fatigue is known to lead to performance errors in locomotive engineers. In particular it is associated with decreased alertness and inattentiveness and as well as increasing the likelihood of actions based on inappropriate schemas, can lead to missed object/signals. Fatigue is known to cause increased reaction times locomotive engineers, and may therefore result in delayed responses to signs and signals. It has also been shown to lead to response omissions, and may therefore be associated with lapses. The general cognitive problems that fatigue leads to imply that it may also be linked to decrements in the strategic planning that is essential to safe train driving. Poorer memory performance induced by fatigue may also leads to decrements in route knowledge and increase the likelihood that knowledge of deviances is recalled. Response omissions and delays at the start and end of duties may be in line with the occurrence of SPADs at these times.

Strong links between fatigue and accidents are not regarded as empirically established in the rail sector.

Professional drivers can be classified according to whether they are involved in long-distance transport or not. Long-distance driving is associated with monotony, irregular driving shifts, a degree of time-pressure and stress, and may also be physically demanding. At times sleeping conditions may be poor. The main challenge for these drivers will be the combined effects of job fatigue and sleep homeostasis exposed by circadian dips. Job fatigue may be a combination of driving fatigue, physical fatigue, and boredom due to waiting. Short-distance drivers are more involved in fatigue caused by driving to delivery deadlines in dense traffic, although there may also be physical fatigue.

Drivers will mostly operate at the skill-based level, but will operate at knowledge- and rule-based level where the route, vehicle or load is unfamiliar. Mistakes, slips and lapses are therefore all common. Several behaviours have been linked to safety (see Table 1). These include violation errors (speeding, seatbelt wearing).

Problems with sleepiness in long-haul or long-distance passenger drivers are well documented, and are due to driving through circadian dips (especially having worked for a long time in the preceding period), and poor and irregular sleep history. Short haul drivers are more fatigued in the afternoon, and poor sleep history and task fatigue may be more of a problem for them, although passive fatigue due to monotony will be more limited. Split shifts may also cause fatigue in bus drivers.

Fatigue has been associated more with skill-based errors than with rule-, knowledge-based errors or violations. Fatigue due to monotony has been associated with less frequent checking behaviour and increased effort.

The main links to safety for drivers have been found for fatigue caused by sleep homeostasis, circadian dips and task-related fatigue due to long, monotonous drives, although the latter remains contentious. The combined interaction of sleep history, time-of-day and accumulated working time is probably all important. Sleep-related accidents involving city drivers is more likely in dense traffic, i.e. monotony is less likely to play a role.

In common with other seafarer roles, watchkeepers have a variety of different tasks and duties, which will depend on ship type and stage in voyage. On merchant ships the central task of watchkeeping, and the particular watchkeeper role, can be integrally linked with a routine watch period, often two a day, each lasting four hours. Outside the prescribed duty period, other physical and administrative tasks need to be performed, and hours may be extended or irregular in the event of unforeseen circumstances. In reality working days and working weeks are often long. Periods of intense effort can alternate with long spells of monotony. The role of watchkeepers as uninvolved system monitors has increased with reduced manning and increased use of technology on the bridge. Regulators have promoted Bridge Resource Management as a way minimize safety problems associated with human resource distribution on the bridge, including those caused by fatigue.

On smaller ships and boats, and in particular fishing vessels, the crew is smaller and watchkeeping roles depend on boat activities. The intensity of the job and ability to rest or sleep on any ship depends on several factors including manning levels, automation levels (lower workload, higher monotony), equipment maintenance needs, administrative demands, environmental conditions (noise, movement, motion, temperature), crew cohesiveness, port call frequency and duration, pay systems and schedules.

Three factor categories affect fatigue: hours of work, sleep history / circadian factors, and exposure to stressful mental or physical conditions. At sea, fatigue has been strongly linked to the particular shift worked, but many other influences have been demonstrated. "Short sea" and fishing vessels and ferries may have particular challenges. Fatigue has been linked to a substantial share of groundings, and may also be linked to collisions.

Fatigue presents several common problems to human transport operators on railways, roads or at sea, but each may have been considered to varying extents depending on the sector researched. Conclusions from the current review are summarized in Table 4. In each sector there is little evidence that any one cause of fatigue *in isolation* has a clear effect on performance. It seems rather that a system of factors interact to cause fatigue. It is this system and the dynamic interaction of its elements that must be surveyed and managed to ensure that the performance and wellbeing of operators is not influenced unduly by fatigue. Combined challenges of fatigue due to poor sleep history (especially irregular shift patterns and fragmented sleep), work at all times of day and sustained task performance appear to be the main challenges that must be accounted for among other factors in the system.

Each type of operator can be challenged by task underload, i.e. having to perform a vigilance task under unstimulating, monotonous conditions, at times of day, often when at drives towards sleep are at their highest. This will present problems in terms of sleepiness and maintenance of cognitive task performance. Problems related to monotony may be worse on some ships, where sleep opportunities can be disrupted, fragmented and short, the watchkeeper cannot choose to stop and rest in the absence of support, and may be physically and mentally tired from an array of other tasks.

However, the problems faced by some drivers on the road are just as great, especially for drivers who perceive that there is insufficient time to stop or rest. Sleep opportunites may also be poor, there may be physically demanding tasks, boredom from waiting, and the driver cannot leave his or her seat. Increasing automation appears to be adding to the problem of monotony and passive fatigue in all transport sectors.

Table 4. A comparison of job aspects, safety and fatigue challenges and fatigue-safety links for operators on rail, roads and at sea.

Role	Job aspects	Safety challenges	Fatigue challenges	Fatigue-safety links
Rail operator	Routine, demanding, monotonous at times. Mostly mental tasks.	Unsafe response to signals and speed limits, may be caused by vigilance problems, multitasking, distractions, incorrect assumptions based on routine, time pressure, monotony.	Unpredictable, irregular shift patterns; work at all times of day; problems at start and end of shift.	Fatigue may lead to reduced alertness and increase inappropriate schema use and response times; may lead to action lapses, forgotten knowledge, poor planning and decision making.
Road driver	Continous vigilance, action often at knowledge- and rule-based, but mostly skill-based levels. Task overload (stimulating city traffic) and underload (monotonous stretches) can be a problem. Mental and sometimes physical tasks.	Failed action execution, poor action execution, misjudgments, perception failures, problems with focus of attention, distraction, incorrect situation assessment (mode error), memory problems, and violations.	Poor sleep history, irregular shift patterns, need to drive through circadian dips (long-distance) or intense traffic (short distance). Long working hours and driving hours violations may also be a problem.	Fatigue leads especially to skill based errors. In monotonous driving with high homeostatic and circadian pressure, it leads to reduced attention, checking and monitoring, and sleepiness behind the wheel. Sleep drives linked to accidents.
Watch-keeper at sea	Continous vigilance, with task underload due to monitoring of reliable system, during watchkeeping. Many other tasks.	Problem with focus of attention and distraction on bridge. Long periods of monotony interspersed by periods requiring rapid action situation awareness. Workload from non-watchkeeping tasks interfere with watchkeeping.	Minimal manning, port calls at different times of day, suboptimal watch systems, poor organization, high demands and conditions on board can each contribute to unpredictable, fragmented, irregular sleep. Exacerbates problems for watch shifts including circadian troughs.	Increased reaction time, reduced attention and recall, poor general cognitive performance, missing critical signals, loss of situational awareness and increased risk of collisions and groundings.

For each type of operator fatigue may pose a particular threat to skill-based task performance, in terms of increase risk of slips, lapses and mode errors. Rail research suggests that the fixed track environment and extreme routine that locomotive engineers can be exposed to makes fatigue-induced mode errors a particular threat. Long-distance road drivers and watchkeepers at sea may face similar challenges, even though they have not been researched to the same extent.

Thus it may not be sufficient to consider that accidents are caused by sleepy operators failing to respond to warning signals. In most cases on the rail and at sea, there will be defenses in place to cope with such incidents. Many fatigue-related safety problems may rather be caused by the influence of fatigue on complex faculties that allow operators to be mindful about emerging situations, assess a range of possibilities and act on emerging situations. In such cases fatigue will not only influence simple attention, but immediate priorities, expectations and the current world model, and the access and salience of knowledge and previous experience (McLeod et al., 2005). Effects of fatigue on reaction time, decision-making and memory may be important in this regard.

Finally, we should also note that task fatigue due to overload may be a particular problem for urban drivers on the road, who may not necessarily have better sleep than other types of operator, according to reports. The task is often cognitively dynamic and complex, demanding rapid response times (braking). In addition, the driving task may not be the main priority. Similar situations can arise periodically for train drivers in station areas, and for ships in busy waters or performing docking manouvres.

9 Summary and implications

Improved operationalization of the complex and abstract phenomenon of fatigue is required to help assess tackle fatigued-related safety problems in human transport operators. Fatigue cannot be distilled to a single dimension, but has multidimensional aspects that do not fully correlate, and describe how it manifests itself in subjective experience, physiology and performance. The impact of these multiple components of fatigue on the operator must be considered in a systems perspective.

Operational definition

We have evolved a broad multidimensional definition of fatigue that is useful for the study of fatigue in human transport operators, and other researchers may wish to converge on this. It is meant as a contextual definition, and it can be used as the basis for narrower operational definitions to be used for specific studies of aspects of fatigue. The definition is as follows.

Fatigue is a suboptimal psychophysiological condition caused by exertion. The degree and dimensional character of the condition depends on the form, dynamics and context of exertion. The context of exertion is described by the value and meaning of performance to the individual; rest and sleep history; circadian effects; psychosocial factors spanning work and home life; individual traits; diet; health, fitness and other individual states; and environmental conditions. The fatigue condition results in changes in strategies or resource use such that original levels of mental processing or physical activity are maintained or reduced.

The definition implies that psychological (experiential) and physiological aspects of fatigue need to be measured in order to understand the state of fatigue. In order to understand the fatigue *process*, we need in addition to characterise the form, dynamics and context of exertion, in addition to performance. The definition also accounts for sleepiness as a component of fatigue. The inclusion of exertion as a cause of increased homeostatic pressure in models of sleepiness explains the overlap between fatigue and sleepiness. Exertion in the face of homeostatic and circadian sleep pressure may also increase sleep propensity, and exacerbate the sleepiness component of fatigue. In fact fatigued states may be revealed in terms of performance decrements in circadian lows, as fatigue becomes too great for the operator to be able to compensate.

Sleepiness is a component of a broader fatigue construct

We understand sleepiness a lot more than we understand other components of fatigue, at operational, theoretical and physiological levels. Based on homeostatic and circadian influences, we can make reasonably successful predictions of average sleepiness for a groups of operators at varying times of the day, after they have followed a given work schedule, or have been given a certain series of sleep opportunities. An obvious question then is why not focus on sleepiness as a safety risk for human transport operators, and ignore the confusing concept of fatigue altogether?

Here are some of the arguments we present against doing this:

1. We wish to understand the effects of sustained work and working while tired on performance, and sleepiness models say little about this.
2. Even though they may not be sleepy, human operators may still be fatigued such that performance or latent performance is affected.
3. Vigilance is a central task for all transport operators, and task-related fatigue can have strong effects on vigilance.
4. We are interested in accounting for how cumulative fatigue related to stress and other energetic constructs may lead to performance reductions.

A new heuristic for thinking about fatigue

Given that we wish to employ the broader concept of fatigue, how should we think about components that are not directly related to sleep drives, i.e. those that are related to sustained activity, time at work and time on task? In particular, our thinking must be structured in a way that accounts for the large variation in time-on-task effects on performance.

Two main models explain variation in time-on-task effects on performance by accounting for the nature of the task and/or the motivational influences on fatigue: the compensatory control model and the dynamic model of stress and attention. These models disagree fundamentally about whether the experience of fatigue is an indicator forecasting a future lack of energetic resources (mental or physical), or a discrepancy between the direction of actual behaviour and desired goals. We note that the latter makes it difficult to distinguish fatigue from stress, but it may be beneficial to consider that concerns about one's own physiological state *and* concerns about misalignment of behaviour and desires may contribute to the fatigued state and thus be limiting for performance. This approach has been assimilated in this report, into a new heuristic for the *process* of fatigue in human transport operators. This heuristic also accounts for:

- sleep drives as an integral component of fatigue
- the role of lower order (subconscious) and higher order (conscious) processes in determining performance
- the role of emotions and feelings linked to fatigue in determining fatigue effects on performance

Surveys should include considerations of motivation and task content

Regardless of stance on the origin of the experience of fatigue, most authors agree that energetic limitations are not directly linked to performance decrements. In other words, when considering how fatigue affects performance, we must attend to the human transport operator's attitude and motivation he or she brings to the task. He or she will be adept at adapting to maintain performance, but that this has certain costs which any survey of fatigue should attempt to account for. These costs may be in terms of latent performance decrements and personal health or quality of life costs. When compensating for performance, we should also consider changes in strategy that an operator chooses to perform the task, and how these subtle changes may have implications for safety.

Any survey should consider that some tasks, especially vigilance, may be inherently fatiguing in terms of performance.

Surveying fatigue

If fatigue is multidimensional, each dimension should ideally be surveyed when assessing fatigue in a sample, as far as this is practical. Self-reports are the most pragmatic way of gathering data, and this is important to consider when surveying human transport operators. Self-reports can be used not only to collect a measure of subjective fatigue states, but as a means of collecting performance data, or data on compensatory strategies, latent performance decrements or health effects. In assessing performance, it is important that reports relate specifically to performance of the task in question.

Most instruments have been developed to collect self-reports on acute subjective fatigue. A taxonomy of fatigue measures strongly suggests that chronic fatigue has been overlooked in the development of survey measures. Some instrument measuring acute fatigue measure exclusively sleepiness, while others tap into various aspects of the broader construct. After review, we conclude that instruments employing several items to assess each of several aspects of fatigue are preferable, and it is important that the instrument defines the period of interest for the respondent. Several popular scales are available, with good psychometric properties. Several scales analyse the experience of fatigue along several dimensions, the most common of which are physical, cognitive and emotional fatigue, and sleepiness. Each subdimension may map on to a general or overarching fatigue dimension. In addition to fatigue scales, scales developed independently to measure alertness should also be considered.

Overall, we regard the SOFI as promising for the measurement of fatigue experience in human transport operators. The SOFI is probably the most well developed scale for occupational fatigue, and different human transport operators may have characteristic subscale profiles, depending on the nature of their job. When assessing different workers we should remember that fatigue that is specifically task-related may be experienced along dimensions that are different from fatigue due to general tiredness and work, and it may be important to capture the task-specific fatigue experience in order to understand the most safety-relevant aspects of fatigue.

Objective measures tapping into the physiological state of fatigue have not yet been used to survey of large numbers of human transport operators. However, methods such as PVT and actigraphy are becoming increasingly accessible, and may be worth considering. Alternatively it may be possible to survey representative subsamples of operators using objective methods. Again, measures of performance should be matched to safety-related performance of interest.

Objective performance measures, health or data on latent performance decrements may be collected at individual or organisational level, and must be considered on a sample by sample basis.

Findings on general performance effects of fatigue

This report also presents the likely effects of fatigue on safety performance for different types of human transport operator, such that researchers can consider which data might best reflect-safety related performance, and which aspects of this performance may be most affected by fatigue.

Sleep deprivation has been found to affect a range of cognitive functions, most notably reaction time and lapses. Slowed and more variable reaction times are found in computer tests and real world driving. Functions affected by sleep deprivation that may be particularly relevant to human transport operators are reaction time, alertness, perceptual skills, decision making, judgments and cognitive slowing. Increased attention deficits and accelerated vigilance decrements may be particularly important.

The implications of these functional decrements caused by sleep deprivation for performance will depend on the task or job activities in question. Monotonous, unstimulating tasks are more likely to make performance vulnerable to functional decrements. Time of day will also influence the extent of functional decrements and related performance outcomes.

Importantly, sleep deprivation may produce impairments that reduces the ability of operators to handle unexpected, challenging situations, and make them more likely to rely on ingrained and inappropriate schemas. The fact that sleep deprived workers may also be more susceptible to distractions increases the likelihood of this happening.

Many studies of the effects of sleep deprivation on performance are carried out on participants who are subject to acute total sleep deprivation. Many human transport operators will suffer from curtailed sleep over the longer term (chronic partial sleep deprivation). Little is known about how the latter affects performance, but we know that there are strong effects on attention and vigilance.

In addition, studies of the effects of sleep deprivation on performance often use participants who may be less motivated to perform than people in real work situations. Thus human transport operators may demonstrate more compensatory effort in the face of sleep deprivation, and the effects on performance may be delayed.

Links have been established between sleep deprivation, circadian lows and accidents, implying the involvement of sleepiness.

Isolating the effects of task fatigue on performance from the effects of homeostatic and circadian influences is often difficult and rarely achieved. However, there is good evidence that sustained task performance results in decrements to sustained attention and functions involved in vigilance, especially where the task is continuous, perceived as boring, is demanding or taxes attentional resources. In terms of real world settings, the following may induce task fatigue for human transport operators: driving on unstimulating, long straight roads; sailing a quiet ship on uneventful, open seas while following the same course; long straight, unstimulating rail stretches. These effects will of course be exacerbated by circadian nadirs and sleep deprivation.

The job of human transport operator may also involve physically or other mentally demanding tasks that exacerbate vigilance performance decrements. Costs of attempting to maintain main task performance, include attentional narrowing, less use of memory, strain and effort, post-task preference for low effort, subjective fatigue and risky decision making. Thus the effects of fatigue on performance of the whole job may be important, as are interactions of other job characteristics, such as supervision levels, on performance.

The effect of task-related fatigue on accidents and injuries is unresolved due to lack of suitable studies.

Safety performance and fatigue in the context of human transport operators

An examination of the human transport operators in the rail, road and sea sectors led to several common conclusions:

- Combined challenges of fatigue due to poor sleep history (especially irregular shift patterns and fragmented sleep), work at all times of day and sustained task performance appear to be the main challenges that must be accounted for.
- Thus a system of factors interact to cause fatigue, and this system and the dynamic interaction of its elements that must be surveyed and managed to ensure that the performance and wellbeing of operators is not influenced unduly by fatigue.
- All operators can be challenged by task underload, i.e. having to perform a vigilance task under unstimulating, monotonous conditions. This can occur at times of day when sleep drives are at their highest. This will present problems in terms of sleepiness and maintenance of cognitive task performance.
- For any operator, fatigue may pose a particular threat to skill-based task performance, in terms of increase risk of slips, lapses and mode errors.
- Fatigue-induced mode errors may be an overlooked threat and cause operators to persist with inappropriate strategies in unforeseen, deviant, demanding or distracting situations.
- Many fatigue-related safety problems may be caused by the influence of fatigue on complex faculties that allow operators to be mindful about emerging situations, assess a range of possibilities and act on emerging situations. In such cases fatigue will not only influence simple attention, but immediate priorities, expectations and the current world model, and access to and salience of knowledge and previous experience. Effects of fatigue on reaction time, decision-making and memory may also be important in this regard.
- Task overload may be a particular problem for some operator roles.

Implications for studying human transport operators

To summarise, this report has the following implications for the study of fatigue in human transport operators:

- Fatigue should be operationalized using the provided definition, and thought about using the heuristic provided.
- Fatigue should ideally be measured in terms of the experience, physiological state and performance
- The experience of fatigue itself should be measured along several dimensions, and supplemented with a measure of alertness.
- SOFI may be particularly useful, i.e. it is well developed and would allow for useful comparisons among different operators, and with other occupational samples
- Cumulative chronic fatigue should not be ignored
- Performance should be measured in a way that is specific to task-related safety
- Motivational aspects surrounding the task or job should also be measured, and related to compensatory strategies, costs to the operator and latent performance decrements
- Where there is a main safety-relevant task, the nature of the task itself should be considered
- The physiological and behavioural methods of fatigue measurement may be difficult to apply in routine operations. In this regard, rapidly advancing handheld technology available to all (especially mobile phone apps) could be considered and/or study of a representative subsample.

- In regarding performance effects, the systemic interaction of sleep history, time of day and time at work or on task should be considered in the context of factors describing the operator's job and non-work/off-duty life.
- For operators that may be sleep deprived, a range of cognitive functions may be challenged, and these may lead to reduced attention, poor detection abilities, vigilance problems, delayed response times, cognitive slowing, poor judgements and lapses; in particular there may be overreliance on ingrained schemas in deviant situations.
- For underloaded operators with task fatigue and little control, there may be problems with attention and vigilance
- Job fatigue will also be associated with slips, lapses, mode errors and, again, the ability to assess and act appropriately in emerging situations that are non-routine.

Finally, when considering how to survey fatigue in human transport operators, we should consider that life outside work (or life off-duty) may also play an important role on fatigue while on duty. Constructs such as psychological detachment from work or work-life balance may be useful in this regard.

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Visiting and postal address:
Institute of Transport Economics
Gaustadalléen 21
NO-0349 Oslo

+ 47 22 57 38 00
toi@toi.no
www.toi.no