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Biomathematical Fatigue Models
Guidance Document

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List of Abbreviations[1]

ATC	Air Traffic Control
ATSB	Australian Transport Safety Bureau
BAM	Boeing Alertness Model
CAA	Civil Aviation Authority, UK
CAO	Civil Aviation Order
CAS	Circadian Alertness Simulator
CASA	Civil Aviation Safety Authority, Australia
CFIT	Controlled Flight Into Terrain
CRM	Crew Resource Management
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration, USA
FAID	Fatigue Assessment Tool by InterDynamics
FAST	Fatigue Avoidance Scheduling Tool
FDA / FDM	Flight Data Analysis / Flight Data Monitoring
FOQA	Flight Operational Quality Assurance
FRI	Fatigue Risk Index
FRMS	Fatigue Risk Management System
ICAO	International Civil Aviation Organization
KPI	Key Performance Indicator
KSS	Karolinska Sleepiness Scale
LOFT	Line Oriented Flight Training
LOSA	Line Operations Safety Audit
MRO	Maintenance Repair and Overhaul organisation
NASA	National Aeronautics and Space Administration
NTSB	National Transportation Safety Board (USA)
PVT	Psychomotor Vigilance Task
SAFE	System for Aircrew Fatigue Evaluation
SAFTE	Sleep, Activity, Fatigue and Task Effectiveness
SMS	Safety Management System
SP	Samn Perelli fatigue scale
SWP	Sleep / Wake Predictor
ULR	Ultra Long Range flight operations
WOCL	Window of Circadian Low

[1] A number of the included abbreviations are explained further in the Glossary.

Preface

This document was commissioned by the Civil Aviation Safety Authority of Australia (CASA) to provide the aviation industry with updated guidance on the application of biomathematical fatigue models for use as optional components of Fatigue Risk Management Systems (FRMS).

In 2010 CASA released a guidance document on Biomathematical Fatigue Modelling (Civil Aviation Safety Authority, 2010)[2], as a resource to assist civil aviation operators electing to integrate biomathematical models as part of flight crew FRMS. This was one step in the move towards a performance-based regulatory framework.

The science and application of fatigue modelling continues to evolve and the current report is designed to update the CASA 2010 guidance document. As with its predecessor, this report includes a survey of the capabilities of currently available biomathematical fatigue models and discusses important considerations regarding the incorporation of such models into an FRMS, but does not address overall FRMS implementation strategies.[3]

This report is intended to assist aviation operators in:

1) Deciding whether to incorporate a biomathematical fatigue model into their FRMS;

2) Evaluating the features and limitations of available models to determine which model is the best fit for their specific operating environment and requirements.

Biomathematical models are tools for predicting crewmember fatigue levels, based on a scientific understanding of the factors that contribute to fatigue. They are an optional component of a broader FRMS. All biomathematical models have limitations that must be understood to ensure their appropriate use within an FRMS. These limitations, along with potential benefits, are discussed in this report.

The information and recommendations provided within this report may also be generally applicable to the use of biomathematical models within the envelope of prescriptive flight and duty time limits, and for non-flight crew personnel.

Seven models were selected for evaluation in this review, based on their current availability and suitability for application within the civil aviation environment. The capabilities and limitations of each model are reviewed and compared, based on a combination of published peer-reviewed and self-reported information from representatives of each of the featured models. The information has been summarised to assist aviation operators to understand and compare the different models. It should be noted, however, that direct independent field evaluation of the models was beyond the scope of this project and has not been conducted. Interested parties should verify all details about the capabilities and suitability of a particular model before deciding to implement it.

Operations within the aviation industry are wide and varied and so not all considerations relevant to every operator's selection of a model are covered here. Operators should therefore consider the information included within this report as a *starting point* for model assessment. A full assessment of model capabilities, validity for intended applications, and considerations such as cost, available training and support services, data format and compatibility with the target operating environment should be pursued directly with model representatives.

Guidance on how to use this document is provided in the next section.

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[2] Civil Aviation Safety Authority. (2010). *Biomathematical fatigue modeling in civil aviation fatigue risk management: Application guidance. Version 1.0, 15 March 2010.* Canberra: Author.

[3] For further guidance on FRMS implementation, the reader is referred to recent publications addressing this topic (Civil Aviation Safety Authority, 2013a, 2013b, 2013c, 2013d; IATA, ICAO & IFALPA, 2011).

1 Introduction

The aim of this document is to provide detailed guidance to aviation operators on the application and use of biomathematical fatigue models. The report is specifically designed to help operators decide whether to incorporate a biomathematical fatigue model into their FRMS and to provide a useful evaluation of the available models to help operators select the model that best fits their requirements.

1.1 Document Structure

This document has nine main sections.

This Introductory section outlines the purpose and structure of the report, introduces the models selected for evaluation, and describes the data gathering and review process used in preparing this document.

Section 2 gives background on the development of material included within this guidance document, with specific reference to the international and local regulatory context for biomathematical models. After setting the context for fatigue risk and safety management, it discusses some important general cautions on the use of biomathematical fatigue models.

Section 3 explains the science behind biomathematical models of fatigue, including: their basis in initial sleep process models; the structure and components of current models; their input data requirements; the output measures; and the data sets on which they have been validated.

Section 4 discusses the limitations of biomathematical models, including their assumptions about the complex relationship between fatigue and safety, the potential of most models to underestimate risk by only considering the effects of acute not chronic fatigue, and the fact that they typically generate group estimates of fatigue rather than accounting for individual variability.

Section 5 describes seven main applications for biomathematical fatigue models: Forward scheduling; Non-scheduled / irregular operations; Work / rest cycles in augmented crew; Evaluation of countermeasures; Individual fatigue prediction; Training; and Safety investigation. The aim of this section is to help potential users select and focus on the applications of highest priority for their organisation / operation.

Section 6 explains the elements of fatigue models, in terms of their internal structures and formulae (‘components’), the variables that can be entered into the models (‘inputs’), and the prediction measures or outcomes that are produced (‘outputs’). The inputs, components and outputs defined in this section are used in Section 8 to compare the seven selected fatigue models in terms of these three features.

Section 7 contains a directory of the seven biomathematical fatigue models, providing identifying information for each model, summarising their objectives, applications and outputs, and listing any particular advantages and limitations.

Section 8 compares the seven biomathematical models according to their features and applications. These comparisons are designed to help potential users select a model that best meets their needs. Information is provided comparing: the main applications of each model (*Assessment Stage 1*) and their components, inputs and outputs (*Assessment Stage 2)*. Finally, the models are compared against a set of higher-level evaluation criteria.

Section 9 summarises the main observations and conclusions contained in this guidance document.

A Glossary and Reference list are also included for further reader guidance.

1.2 How to use this document

As an updated version of the CASA 2010 guidance document on biomathematical fatigue modelling, this document may include information that is already familiar to some readers. Figure 1 shows the sections in this document and highlights those sections that will be of most relevance to users who already have some understanding of the FRMS background and the science of biomathematical models and their limitations, and are looking to choose and implement a 'best fit' model for their needs. These experienced users are directed from this Introduction to Section 5 to review the model applications, then to Section 7 for details of the models reviewed in this document, and finally to Section 8, to compare and evaluate models.

Users who are new to the field of biomathematical modelling and wish to understand the models and their potential for use as part of an FRMS should proceed through the whole document, from the Introduction to Section 2 (Biomathematical fatigue models in context, which includes an important review of cautions on the use of biomathematical models), Section 3 (The science behind fatigue modelling) and Section 4 (Model limitations). Users who wish then to select a model that meets their specific requirements should then read the remaining sections in order. Section 5 describes model applications, Section 6 contains detailed explanation of the model characteristics and Sections 7 and 8 describe, review and evaluate the various available models to assist users in making an informed choice.

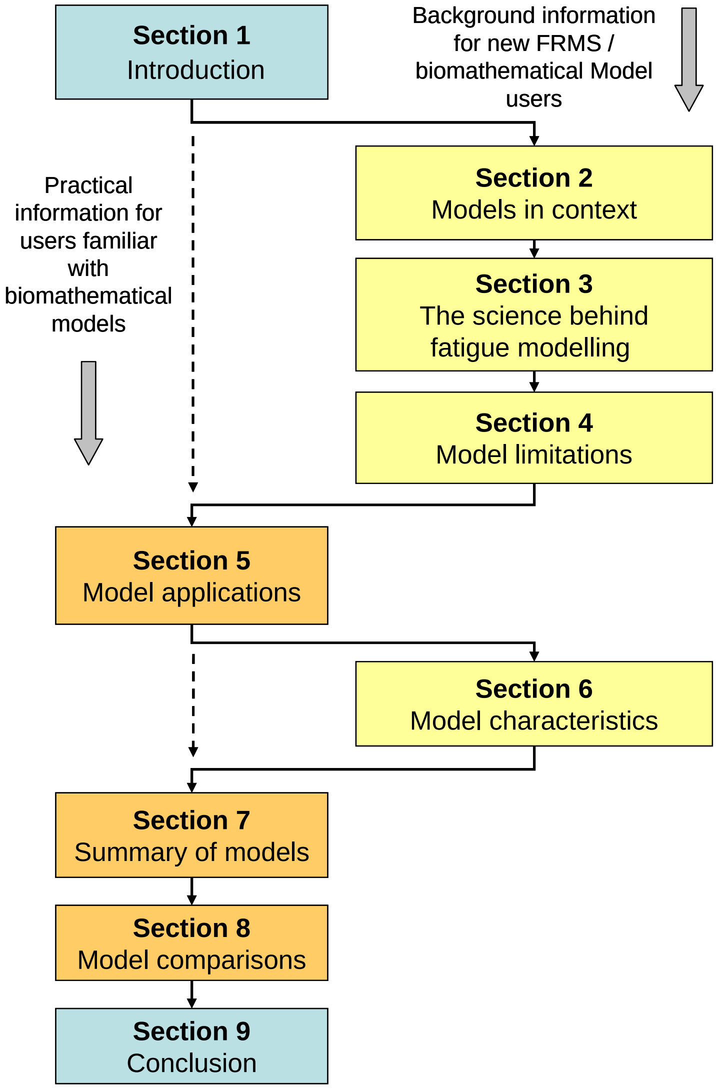

Figure 1
Document Outline and Recommended Use

1.3 Selected Models

Seven biomathematical models were selected for consideration in this guidance document, on the basis of the following criteria:

- Availability of peer review papers. This was the first priority criteria as it affords the best guarantee of the scientific value of the model;
- The model is integrated into a usable computer application and is currently available for use; and
- The model is regarded as applicable for use in the aviation industry.

The seven included biomathematical fatigue models are:

- The Boeing Alertness Model (BAM);
- The Circadian Alertness Simulator (CAS);
- The Fatigue Assessment Tool by InterDynamics (FAID);
- The Fatigue Risk Index (FRI);
- The System for Aircrew Fatigue Evaluation (SAFE);
- The Sleep, Activity and Task Effectiveness Model and associated Fatigue Avoidance Scheduling Tool (SAFTE-FAST); and
- The Sleep Wake Predictor (SWP).

It should be noted that the above list includes two models that were not available for review for the 2010 report, the BAM and the FRI. It is also noted that one model reviewed in the 2010 report, the Interactive Neurobehavioural Model (INM) has been excluded as it is more applicable for research purposes and is not currently available for operational use.

Section 8 of this report compares the capabilities and limitations of each of the selected biomathematical models.

1.4 Data Gathering

Information on the selected models was gathered from a variety of sources. These included:

1. Publically available information sourced from the internet, including websites relating to the models and their suppliers, product reviews and media articles;
2. Further details provided by model representatives / suppliers on request, such as user guides, tutorials and technical fact sheets;
3. Peer-reviewed studies and method reviews located during a literature search; and
4. Responses to a structured questionnaire forwarded to representatives / suppliers of each of the models.

The information gathered was then reviewed and analysed by the project team.

A draft guidance document was prepared and relevant details were then subjected to a two-stage review process by model representatives / suppliers, where they had the opportunity to correct any inaccurate information and provide further details and feedback. The draft and final guidance documents were also reviewed by CASA prior to release.

2 Biomathematical Models in Context

This section provides background on the development of material included within this guidance document, with specific reference to the international and local regulatory context for biomathematical models, and discusses some general cautions on their use.

2.1 Regulatory and FRMS context

Aviation has always been an industry requiring workers to attend work and perform their duties around the clock. Whether this involves mechanics and technicians preparing an aircraft for flight, pilots and cabin crew operating the flight, or air traffic controllers, aviation rescue and fire officers, ramp workers and others who are required to ensure the safe and effective outcome of the operation, starting and finishing work at non-standard hours and/or across different time zones are a longstanding regular feature of aviation work.

It has long been recognised that the risks associated with fatigue must be identified and managed if safety is to be assured. In this context, the International Civil Aviation Organization (ICAO) defines fatigue as:

> *A physiological state of reduced mental or physical performance capability resulting from sleep loss or extended wakefulness, circadian phase, or workload (mental and/or physical activity) that can impair a crew member's alertness and ability to safely operate an aircraft or perform safety related duties.*
>
> (International Civil Aviation Organization, 2012a, p. xii).

Historically, the civil aviation industry has regulated fatigue risk through the prescription of maximum duty times and minimum rest times within the framework of Flight and Duty Time Limitation (FTL) schemes. As the industry has grown so have the numbers of people employed and the requirement for effective means of managing and scheduling the working hours of those personnel. In many cases, existing FTL limits have been in place for decades and have not evolved as technology, work practices and scientific knowledge have developed. In recent years the aviation industry has been moving from traditional crew scheduling practices, based on prescriptive duty time limitations, to the adoption of performance-based crew management systems and techniques. Performance-based legislation specifies what is to be achieved, but does not dictate how the outcome must be achieved (Civil Aviation Safety Authority, 2010). The means of compliance is left largely to the discretion of the operator, with guidance and audit functions provided by a proactive regulator.

CASA's *Civil Aviation Order (CAO) 48.1 Instrument 2013* (Civil Aviation Safety Authority, 2013d) was introduced in April 2013 and is the new regulation dealing with fatigue management of flight crew within the Australian aviation industry[4]. Under CAO 48.1, aviation operators and flight crew have a shared responsibility to manage fatigue. The new CAO adopts a three-tiered approach to fatigue management, ranging from a prescriptive basic level, through a mix of prescription and risk management, to a fully developed FRMS (Civil Aviation Safety Authority, 2013c). The intention of the new CAO is to allow operators and individuals to better manage the risk of fatigue and the alertness levels of flight crew, reflecting changes to the aviation industry and advances in knowledge about fatigue management.

Safety Management Systems (SMS) are now required for operators in all elements of the global aviation system. In recent years ICAO has issued the Safety Management Manual 3rd Edition (SMM; International Civil Aviation Organization, 2012b) and the new ICAO Annex 19 on Safety Management (International Civil Aviation Organization, 2013), which integrates safety management guidance previously included in a range of other documents (including ICAO Annexes 1, 6, 8, 11 and 14).

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[4] While CAO 48.1 currently only deals with flight crew, similar new legislation applicable to cabin crew and air traffic controllers is under preparation.

These documents describe the requirement for aviation operators to establish organisational structures, accountabilities, policies and procedures that effectively identify hazards, analyse and mitigate risks and provide the organisational structure and framework to manage safety. Human fatigue is one aspect of operational safety, and systems for managing the risk associated with fatigue form part of an effective SMS. While prescriptive FTL schemes have traditionally been used as the primary fatigue risk control method, Fatigue Risk Management Systems (FRMS) have evolved as an alternative approach that allows operators to draw upon the growing body of fatigue science and local operational experience for improved fatigue risk management.

FRMS have been the subject of considerable discussion and productive effort within the global aviation community in recent years. FRMS guidelines have been developed and published by a range of organisations, including the products of a global joint industry FRMS Task Force established to provide FRMS application guidance for airline operators (IATA, ICAO & IFALPA, 2011) and regulators (International Civil Aviation Organization, 2012a). Many national regulators, including Australia's Civil Aviation Safety Authority (CASA), have also been active in providing FRMS information and guidance for local industry (Civil Aviation Safety Authority, 2010; 2013a; 2013b; 2013c).

ICAO defines an FRMS as:

> *a data-driven means of continuously monitoring and maintaining fatigue related safety risks, based upon scientific principles and knowledge as well as operational experience that aims to ensure relevant personnel are performing at adequate levels of alertness.*
>
> (International Civil Aviation Organisation, 2012a, p. xiii)

In practice, an FRMS is a holistic risk management approach that includes hazard identification, risk assessments, mitigation strategies, training and education programs, fatigue monitoring systems, and continual adaptation processes for reflecting changing circumstances and feedback. Operationally it may also be viewed from a prevention, prediction, detection, and intervention perspective (Civil Aviation Safety Authority, 2010).

An FRMS can be used to support the safe application of existing local FTL requirements by applying operational experience and the latest fatigue science to interpret and, at times, vary requirements with the goal of increasing crew alertness and performance.

While not an essential component of an FRMS, biomathematical models of human fatigue are a useful tool, incorporating aspects of fatigue science into scheduling through predictions of fatigue risk levels, performance levels, and/or sleep times and the provision of opportunity for rest (Civil Aviation Safety Authority, 2010). Biomathematical models are sets of equations that quantitatively predict a fatigue risk metric or corresponding output, based on factors such as sleep history, time of day and workload. The power of these models lies in their ability to embed scientific research and knowledge gained from empirical observations into generalised prediction tools (Civil Aviation Safety Authority, 2010).

Biomathematical fatigue models have limitations, however, which must be adequately recognised and considered by users. Fatigue model predictions should never form the sole means upon which operational decisions about fatigue risk management are made. The limitations of currently available fatigue models include a restriction to predicting risk probabilities for a population average rather than immediate or accurate fatigue levels of specific individuals, incomplete description of all fatigue physiology factors, qualitative data being misinterpreted as quantitative data and limited validation against aviation specific data. Due to these limitations and the relatively recent introduction of biomathematical fatigue models to civil aviation, a cautionary approach should be taken. FRMS should be designed as comprehensive, multi-layered systems, in which biomathematical models, when used, provide a supporting role (Civil Aviation Safety Authority, 2010). The limitations of biomathematical fatigue models and cautions on their use are discussed further in Section 2.2 and Section 4.

When used appropriately, however, with an understanding of their limitations, biomathematical models provide a mechanism to quantitatively incorporate some of the latest data-driven, scientific knowledge into an FRMS. The following section discusses some general cautions regarding their use.

2.2 Cautions on the use of Biomathematical Models

The currently available biomathematical fatigue models suffer from several important limitations, as noted here and discussed in further detail in Section 4 of this report. It is important at the outset of a discussion on the use of these models that the required cautions be highlighted.

Biomathematical fatigue models are designed to take into account a range of factors relating to fatigue and to convert these into simple numerical scores representing fatigue risk. These scores can be used for performing comparisons (of schedules, for instance) or for evaluating a schedule against an upper fatigue limit. However, it is vital to avoid overly simplistic interpretations of the numerical estimates provided by the models.

Specifically, it is essential for any specified upper limit for fatigue scores to be validated in the operational environment in which they are to be used. The failure to validate limits or 'cut-off' scores in this manner could result in practices that undermine the quality of the FRMS and result in operational staff having minimal confidence in the system. In the worst case overreliance on biomathematical models could result in an FRMS that actually degrades fatigue management (Civil Aviation Safety Authority, 2010).

When a biomathematical model is included in an FRMS, complementary strategies to pro-actively identify and manage fatigue must also be considered. Flight crews and operational decision makers need to be educated to interpret the biomathematical model's output appropriately. The outputs of such models can give the illusion of being precise and quantitative despite the fact that they simply predict a qualitative measure such as subjective fatigue. Education, audits and the use of additional objective measures should ensure that a balanced view of the opportunities and limitations of models is maintained within an organisation's fatigue risk management culture and operational practices. Scores derived from biomathematical fatigue models cannot provide a "green light" for operational safety, but should rather be used as one of a number of risk management controls and complemented, for example, by crew fatigue monitoring and practices for ensuring adequate rest and sleep (Civil Aviation Safety Authority, 2010). Finally the use of a model within an FRMS should be an iterative process, with fatigue measurements, task errors and incident data collected and used to refine both the model and the overall FRMS.

3 The Science Behind Fatigue Modelling

Most of the models included in this updated guidance document found their origin in Borbély's original model of sleep regulation (Borbély, 1982). This model, developed on the basis of many laboratory experiments, was intended to explain both the timing and duration of sleep as a result of the interaction between two processes:

- Process S (Sleep), also called homeostatic pressure, where sleep onset occurs when process S reaches a high threshold (H) and wake-up occurs when S drops below a low (L) threshold. During sleep, process S decreases in an exponential fashion. Process S is therefore directly related to sleep loss and produces the so-called "sleep pressure" that builds up over time awake. Lack of sleep and/or extended duty time directly increase process S.
- Process C (for Clock/Circadian) is a sinusoidal function that programs sleep to occur during night time and to stop during the daytime. The duration of this pattern is around 24 hours and is called the Circadian Rhythm. Whereas this process has its own internal period (slightly greater than 24 hrs), it is influenced by external factors – the "time givers" such as the light / dark cycle of the local environment. This process operates independently from the time awake which is associated with Process S. Process C is directly impacted under certain conditions typically met in aviation such as rapid time zone transition and/or irregular hours of work and night duties.

It is worth noting that Borbély's 2-process model was entirely focused on sleep and was not intended to model fatigue or alertness. The Three-Process Model of Alertness (TPMA; Åkerstedt & Folkard, 1995, 1996) extended Borbély's initial model by predicting the level of alertness and by adding the process W (Waking), relating to sleep inertia. Sleep inertia refers to the transient state of lowered arousal occurring immediately after awakening from sleep and producing a temporary decrement in performance (Tassi & Muzet, 2000). The TPMA estimates sleep and predicts alertness as depicted in Figure 2 below.

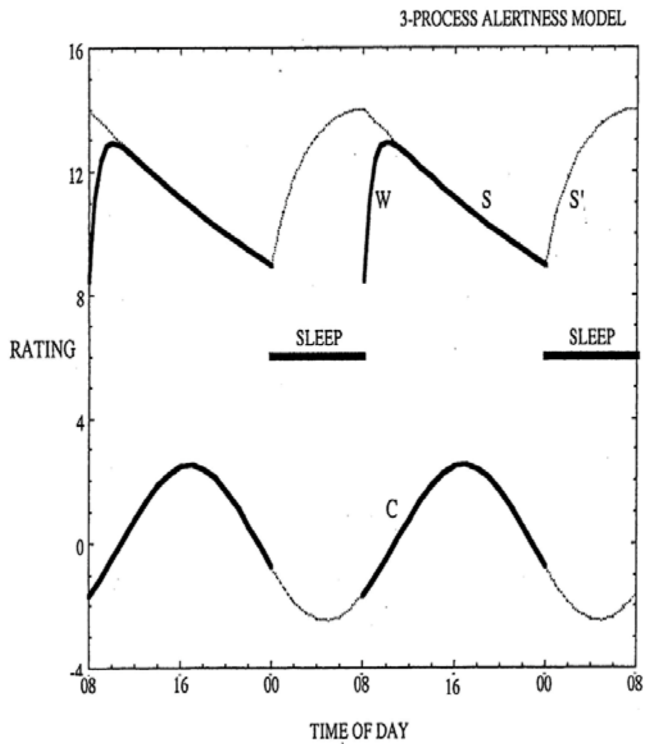

Figure 2
The Three-Process Alertness Model
(from Åkerstedt & Folkard, 1996)

3.1 Model structures

Most biomathematical models covered within this guidance document are based on 2- or 3-process models, and may also be 'task related', in that they consider aspects of the type of task/s to be performed during the work period. An exception is the Fatigue Risk Index (FRI), which is based instead on empirical data from shiftwork and aviation. This model was constructed from three separate components: a cumulative component based on the pattern of work leading up to any given shift; a duty-timing component concerned with the effect of start time, shift length and the time of day; and a job type/breaks component, which relates to the task or activity performed and the breaks scheduled during the shift.

A comparison of the main underlying scientific background for each of the selected models is depicted in Table 1.

Table 1
Comparison of the main underlying scientific background

Selected Model	Main underlying scientific background
BAM	3-process model + task related
CAS	2-process model + task related
FAID	2-process model + task related
FRI	Cumulative, duty time and job type/breaks data from aircrews, train drivers and laboratory studies
SAFE	3-process model + task related
SAFTE-FAST	2-process model
SWP	3-process model + task related

3.2 Input data requirements

The inputs to a biomathematical fatigue model are the factors that need to be provided to enable the model to determine output predictions (Civil Aviation Safety Authority, 2010). Two types of information are generally required to predict fatigue: work-rest schedule and/or sleep data. Sleep data can be obtained from either subjective data (e.g., personal sleep log) or from objective data, most frequently from an actiwatch.

The literature generally distinguishes two types of biomathematical fatigue model depending on their required input (Kandelaars et al, 2005, Dawson et al, 2011):

- One-step models, where fatigue can be directly predicted from the input sleep-wake data (i.e. actual sleep data) in a single step.
- Two-step models, where the input work-rest pattern is used to estimate the sleep-wake pattern, which is in turn used to predict fatigue.

This classification is useful in that it determines whether the model derives predictions solely from the work-rest pattern, or whether it permits actual sleep-wake data as an input to refine predictions. The distinction is also important because there has been much more validation testing conducted for the one-step models than for the two-step models (Dawson et al, 2011).

A comparison between various biomathematical models (Van Dongen, 2004) found that one-step models produced fairly similar predictions to one another, although they have a tendency to underestimate fatigue in the case of chronic partial sleep deprivation resulting from reduced sleep over several days. The two-step models show more marked differences in model outputs due to their inability to account for differences in sleep strategy caused by factors such as social interaction during scheduled break or rest periods. Of the models reviewed in this document, FRI and FAID are classified as two-step models, while the others are one-step models, with the capacity to predict fatigue directly from actual sleep data. Where actual sleep data is not incorporated, they function as two-step models.

Other types of input might also be considered to make predictions of fatigue risk more accurate and further customised. One of the frequently observed limitations of most biomathematical models is that they predict fatigue for the ‘average’ person, without taking into account individual differences and the type of tasks or work context involved. Two types of additional input that can be considered are:

- Task/context related inputs, such as time zone transitions, the number of flight sectors operated within a duty cycle, the workload or the level of attention required, the frequency and duration of scheduled breaks.
- Inputs related to an individual, such as whether the person is a ‘morning’ or ‘evening’ type, their habitual sleep length, commuting time to work location, and other work activities not reflected in the roster.

3.3 Fatigue estimate outputs

The data outputs or metrics of biomathematical fatigue models reflect the range of input data and calculations involved (Dawson et al, 2011). From the user perspective, the outputs of the models are very important features as they are used by the organisation to evaluate and make critical decisions in managing the hours of work for employees. Therefore it is crucial that biomathematical model users understand the underlying significance of these metrics. The interpretation of the metrics will be dependent on the type of application or the question/s that need to be addressed by the model. For example, the relative comparison between different schedules does not require drawing an absolute threshold (Rangan & Dongen, 2013). However, if the question is whether a schedule is associated with an acceptable level of safety, it requires the definition of an absolute value that separates what is acceptable from what is not.

While the primary aim of most of the models selected is to predict fatigue, several additional metrics (Gundel et al, 2007) have been added and therefore most models are able to provide a range of outputs. In practice, the critical aspect of these metrics is their ability to predict an estimated *risk level* from *fatigue or sleep* data.

As already mentioned, the initial 2-process model was designed to predict the timing and length of sleep. Most of the selected models provide a sleep time prediction from which fatigue risk is inferred. Sleep prediction is based on the interaction of the homeostatic and circadian components. These sleep time estimates are useful in predicting fatigue, but can also be used in some specific applications such as the pre-planning of in-flight rest in augmented crew flights. This was the case for the validation of the first Ultra Long Range flights introduced from Singapore to Los Angeles and Singapore to New York, for which the SAFE model was used to determine the optimal crew rest timing and duration (Spencer & Robertson, 2007).

Most of the biomathematical models provide a fatigue or alertness prediction value over a given work period. These values are generally expressed on a subjective scale. The most commonly used scales are the Karolinska Sleepiness Scale (Åkerstedt & Gillberg, 1990) and the Samn Perelli fatigue scale (Samn & Perelli, 1982).

The ***Karolinska Sleepiness Scale (KSS)*** is a one-dimensional scale ranging from 1 (“very alert”) to 9 (“very sleepy, great effort to keep awake”). It has been validated against objective measurement of sleepiness such as electroencephalographic (EEG) and electrooculographic (EOG) activity (Åkerstedt & Gillberg, 1990) and performance evaluation (Kaida et al, 2006). A value of 7 or higher on the KSS is associated with intrusions of sleep and an increased risk of impaired performance. The KSS is the metric used by the SWP model. The FRI model estimates the probability (multiplied by 100) that fatigue will reach a value of 7 or higher on the KSS (Folkard et al, 2007).

The ***Samn Perelli (SP)*** is a 7-point scale with possible scores ranging from 1 (“fully alert, wide awake”) to 7 (“completely exhausted, unable to function effectively”). This scale has been validated and widely used in aviation (Samn & Perelli, 1982; Samel et al, 1997) and is one of the metrics provided as an output of the SAFE model. The authors define values of 5 and 6 on this scale as ‘Fatigue Class II’ where “flying duty is permissible but not recommended”. A value of 7 is considered as ‘Fatigue Class I’, i.e., “Severe fatigue. Performance definitively impaired. Flying duty not recommended. Safety of flight in jeopardy.”

While these subjective scales have the advantages of being easy to use in an operational environment and correlating well with decisions by crew to report fatigue, there are two shortcomings regarding their use in biomathematical models. The first is that the two scales are often referred to as if they were interchangeable, although it is worth noting that their items do not always relate to the same state. The highest value of the KSS, for example, relates to a very low alertness level (“great effort to keep awake”) while the highest value of the SP scale is more associated with an extreme level of fatigue (“unable to function effectively”).

The second issue relates to the relevance of these fatigue scales to safety. In fact, a specific level of fatigue cannot produce a specific level of risk independently of the demand associated with the task. Rather than taking an absolute threshold, Rangan and Van Dongen (2013) proposed an alternative approach using the SAFTE model. This was based on the duty time spent below the fatigue threshold and the distance of the fatigue prediction from the threshold. They claimed that this metric could be useful for evaluating thousands of scheduling options in schedule optimisation tools.

Because of these limitations, research has been conducted specifically to develop metrics more adapted to the real world (Dean et al, 2007) and with a greater degree of operational relevance and acceptance (Fletcher & Dawson, 1997). For example, Hursh et al (2004) developed specific metrics calibrated to operational demands such as that of cognitive effectiveness. This metric is derived via the use of the Psychomotor Vigilance Task (PVT), a widely used reaction time test in laboratory settings and in the assessment of neurobehavioural performance in real world activities. Cognitive effectiveness is interpreted as the inverse of fatigue and ranges in score from 0 to 100. This specific output is integrated, together with other metrics of performance, into the SAFTE model. This metric has been correlated with the risk of railway accidents attributed to human factors contributions (Hursh et al, 2011). In 2009-2010 SAFTE was also validated in the context of commercial aviation operations when it was employed to successfully predict fatigue-induced PVT impairments (on performance aspects such as *effectiveness, reaction time, speed, lapses,* and *false starts*) in a broad field study of airline cabin crew (Roma et al, 2012). The operations covered both domestic and international flights in network, low cost and regional carriers. In a study of pilot shift schedules and performance, Stewart and Abboud (2005) found that FAID provided a useful means of predicting cumulative fatigue effects, with performance trends correlating soundly with FAID fatigue exposure indicators.

Similarly, the FRI provides a separate risk estimate, which is the estimated relative risk of an accident or injury occurring during a particular shift (Folkard et al, 2007). A level of one represents the average risk on a typical 2-day, 2-night, 4-off schedule, involving 12-hour shifts starting at 07:00h and 19:00h. A value of two represents a doubling of the risk relative to this schedule.

Even when the various models and scales have been validated against fatigue or effectiveness measures, the link between fatigue and safety is not easy to establish, especially in a complex sociotechnical system such as aviation (see Section 4.1 for a further discussion on fatigue and safety).

Thus, even though the recent developments in biomathematical models have produced more and more sophisticated outputs or metrics, their interpretation within the framework of an FRMS has to be considered with care as they provide, at best, only an approximation of the actual risk.

3.4 Data Sets and Validation

The data sets used to develop a model affect the scientific validity of its risk predictions for specific operational tasks and the range of operating conditions over which its predictions can be considered relevant. Ideally, civil aviation fatigue risk models would be developed based on large data sets of embedded task performance measurements (from flight data collection systems such as FOQA [Flight Operational Quality Assurance], for example) as well as incident and accident rates from flight crew operating over a range of flight durations, time zones and operating conditions equivalent to those that the model may be used for. In practice, the difficulty of measuring operational task performance, the relatively low rates of aviation accidents, and the cost of data collection and analysis present barriers to such an approach to model validation (Civil Aviation Safety Authority, 2010).

The scientific foundation for most fatigue model development has come from laboratory experiments, in which the temporal profile of fatigue for healthy subjects under imposed sleep restriction or simulated time zone shifts is measured using objective neurobehavioral tests (e.g., reaction time, psychomotor performance, etc) and/or self-report questionnaires (e.g. subjective sleepiness scales as described in Section 3.3 above). Direct relationships between test measures and risks for specific operational tasks have not been widely established, however objective measures such as decrements in test performance are generally regarded as good indicators of factors that will increase the relative likelihood of error risks for a wide range of tasks (Civil Aviation Safety Authority, 2010).

To date several of the selected models have been validated using data from aviation specific environments and this potentially increases their validity and relevance. Recent technological developments have seen the suppliers of one of the selected models utilise ‘crowdsourcing’ to facilitate large-scale data collection within the aviation environment. The concept involves inviting airline crew globally to download, install and utilise a free ‘smartphone’ application (app) then upload their individual data to the supplier for research purposes. While this form of data collection may present some unique challenges, it is an innovation that has the potential to yield large amounts of relevant data for future validity studies and similar approaches are likely to increase in popularity as technology evolves. The use of this technology for individual monitoring and prediction of fatigue is discussed in Section 5.5.

4 Limitations of Biomathematical Models

This section provides a detailed discussion of the limitations of biomathematical fatigue risk models.

4.1 From Fatigue to Safety

From an operational point of view, an individual crew member's level of fatigue is not of direct concern, provided that they perform their duties in a safe and effective manner. Biomathematical models of fatigue essentially make the tacit assumption that changes in levels of fatigue will be paralleled by similar changes in risk, but the available evidence suggests that this may not always be the case. It is obviously true that if an individual's level of fatigue is such that they fall asleep, the risk of failing to respond appropriately when required will be high. The *Herald of Free Enterprise* maritime disaster (Department of Transport, 1987) and the grounding of the Panama registered *Peacock* cargo vessel on the Great Barrier Reef (Marine Incident Investigation Unit, 1997), were both attributed to personnel totally failing to respond because they were asleep. However, most accidents seem to occur while the worker is awake and are linked with slow or inappropriate responses rather than a total failure to respond.

The considerable and diverse evidence relating fatigue to safety was reviewed in detail by Williamson et al (2011). These authors considered the impact of three categories of potential sources of fatigue, namely homeostatic factors (e.g., time since sleep), circadian influences (e.g., time of day) and the nature of the task (e.g., duration, workload and monotony) on (i) actual accidents and injuries and (ii) performance decrements that might plausibly result in accidents or injuries. The results concerning homeostatic influences were fairly straightforward and consistent: the longer someone had been awake for, or the shorter the duration of their sleep period, the higher the risk of accidents and injuries and the greater the performance decrements. Thus, for example, Connor et al (2002) found that after adjusting for demographic variables, drivers who had slept for five hours or less the previous night were 2.7 times more likely to be involved in a car accident than those who had slept for more than five hours. Likewise, a meta-analytic review by Pilcher and Huffcutt (1996) showed that the performance of sleep-deprived subjects was poorer than that of non sleep-deprived control groups, although there was a considerable variation in the magnitude of the effect across studies.

The evidence concerning circadian influences is, however, rather more complex. It is well established that both subjective ratings of fatigue and objective sleep measures such as sleep latency show marked circadian rhythm effects with a maximum effect occurring between 03:00 and 05:00 hours. However, reviewing the available evidence Folkard et al (2006) concluded that, after correcting for exposure, accident and injury propensity reaches a rather earlier maximum at about midnight. Mustard et al (2013) confirmed this earlier than expected risk peak in a recent study of work injury risk by time of day. Indeed it is noteworthy that major industrial accidents such as the Exxon Valdez, Bhopal, Chernobyl and even Three Mile Island occurred rather earlier in operator shifts than the 'normally' expected time for the greatest fatigue effects (Mitler et al 1988). Thus the risk of accidents and injuries would appear to reach a maximum somewhat earlier during the night than does fatigue, although the underlying reason for this is unclear. With regard to performance measures, laboratory studies of circadian rhythms have obtained rather mixed results with some measures of performance showing a direct circadian component while others would appear to only do so in combination with homeostatic factors.

In their recent comprehensive review, Williamson and colleagues (2011) investigated the significant body of research linking fatigue and safety outcomes in detail. They observed that, while fatigue is identified in many countries as a contributing factor to a 'significant' proportion of road accidents, estimates of the role of fatigue vary considerably (from 1 to 20%), and they are in fact merely estimates, often based on criteria that exclude other factors rather than definitively identifying the contribution of fatigue (Williamson et al, 2011, p. 498).

The review conducted by Williamson et al (2011) followed the framework shown in Figure 3 below, first looking for evidence of the effects of various fatigue related inputs (circadian, sleep homeostasis and task-related influences) on fatigue and safety outcomes, then examining evidence for each of these influences on performance capability, before finally summarising evidence for the link between performance and safety outcomes.

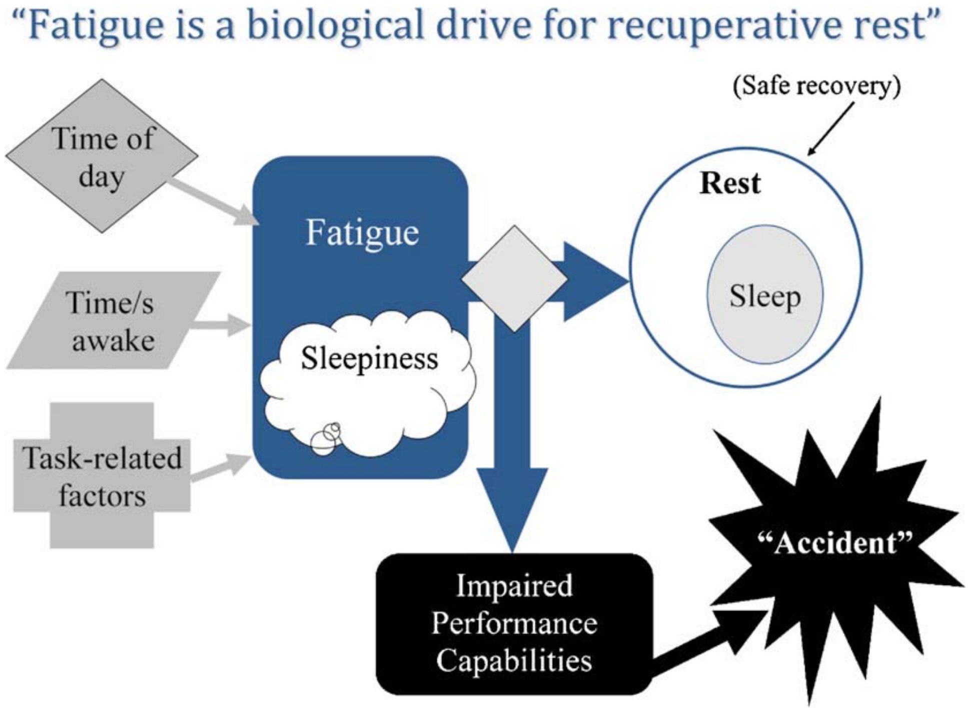

Figure 3
Conceptual model of the relationship between fatigue and safety
(from Williamson et al, 2011)

Williamson et al (2011) detailed clear evidence across multiple studies identifying links between sleep homeostatic factors (including sleep deprivation and time since waking), impaired performance and increased accident involvement. The relationships between both task-related performance decrements, and circadian-related fatigue influences, and safety outcomes were however less clear. Both areas were identified as requiring further careful research and the development of enhanced methodologies and measures in regard to the objective assessment of fatigue.

In short, biomathematical models of fatigue may prove good predictors of the homeostatic component of transient variations in risk, and perhaps even the task demands component where this is included in the model, but are likely to perform less well when estimating the circadian component. Nor do any of the models really attempt to define what an "acceptable" level of fatigue, or any other output, might be. Thus, as they stand the models can be used effectively to compare the relative merits of two or more work schedules, but cannot definitively answer the question as to whether a particular work schedule is acceptable or safe. One obvious reason for this failure is that the level of fatigue or risk that is deemed acceptable will clearly depend on the hazard/s associated with the operation. What may be an acceptable level of fatigue risk in relation to an operator for agricultural crop spraying might be totally unacceptable in the context of operating a large passenger-carrying airliner.

As observed above, in aviation, the link between fatigue and safety is particularly difficult to establish because of the very low accident rate and the complexity of accident aetiology (Amalberti, 2001). In fact, multiple layers of operational defences (cockpit and ATC task automation, checklists, Crew Resource Management strategies, Standard Operating Procedures, etc.) reduce the probability of having an aviation accident attributable to a single cause (here a decrease in human performance due to fatigue; Gander et al, 2011). These operational defences or barriers are used by aircrew as protection strategies against the detrimental effects of fatigue (Dawson et al, 2011) as was observed in a simulator study of line crews conducted at a major airline (Petrilli et al, 2006). The use of these strategies could explain the non-linear relationship between safety-related indicators and fatigue-related indicators. In the context of regional flights, Cabon et al (2012) found that crew operating under reduced rest provisions (a minimum of 7 hours 30 minutes instead of the standard rest of 13 hours between shifts), had a decrease in the frequency of Flight Data Monitoring (FDM) events (of all severity levels) for the duties associated with the highest risk of fatigue. However, the same study found that when the risk of fatigue was elevated, more serious FDM exceedance levels were likely to occur.

4.2 Chronic Effects of Hours of Work on Safety

There are two lines of evidence that suggest that biomathematical models may grossly underestimate risk, simply because they consider only the acute effects of work schedules and not the chronic ones. The first of these concerns the chronic impact of work schedules on performance capabilities. Cho et al (2000) identified cognitive performance deficits and higher cortisol levels in airline cabin crew with more than three years of flying experience, when compared with a matched group of ground crew working for the same company. In a subsequent study, Cho (2001) compared two groups of airline cabin crew with different jet-lag (circadian dysrhythmia) recovery periods and found that short recovery intervals (≤ 5 days) were associated with a range of symptoms including lower cognitive performance, higher salivary cortisol levels (related to psychological stress) and a smaller volume of the right temporal lobe. The findings indicated a cumulative effect of chronic exposure to circadian disruption on cognitive function and the underlying cerebral structures.

Similarly, Rouch et al (2005) reported a cross sectional study of a large sample of male industrial workers in which they found cognitive deficits among those who had been exposed to shift work, when compared to those with no exposure. They also reported a decrease in memory performance related to the duration of exposure to shift work. These effects were independent of self-reported age and sleep quality, suggesting that chronic exposure to circadian desychronisation underlay the observed cognitive impairments.

Ozdemir et al (2013) subsequently demonstrated that shift workers score lower than their day worker counterparts on a wide range of cognitive performance measures, particularly that of working (short-term) memory. In contrast, Devore et al (2013) failed to find evidence of a chronic impairment of performance in retired nurses who had worked shifts, but this failure may reflect the fact that most of the nurses involved in their study had been retired for at least 10 years. Supporting these findings, Tucker et al (2011) and Marquié et al (in preparation) report on analyses of a longitudinal study in which there was not only evidence that the extent of cognitive impairment depended on the duration of exposure to shift work, but also that cognitive abilities recovered during retirement from shift work, such that those who had been retired from shift work for more than 10 years showed no deficit relative to those who had never worked shifts.

The second line of evidence concerns the risk of occupational injuries to shift workers on rotating shift systems relative to that for day workers. A number of epidemiological studies have reported an increased risk for those on rotating shift with the extent of this increase depending, at least in part, on whether the rotating shift system included a night shift (e.g. Fransen et al 2006).

When employed to evaluate the acute effects of work schedules, most biomathematical models cannot estimate the increased risk of occupational accidents and injuries on rotating shift systems relative to that involved for day work. However the Risk Index within the FRI can be used to do so. In order to demonstrate this Tucker and Folkard (2013) used the FRI to estimate the increased risk of occupational accidents and injuries on a range of commonly used rotating shift systems, with and without night work, and then compared the averaged estimates with the averaged values obtained in epidemiological studies. They found that the FRI accounted for only 18% of the increased risk on rotating shift systems without nights, but for 30% of the increased risk on rotating systems that included nights.

Since there are no practical objective measures of fatigue, it is not possible to perform a similar analysis of the contribution of acute effects to the overall fatigue associated with work schedules. Nevertheless, there is evidence that shift workers habituate to a lowered level of general well being, as reflected in their scores on depression and anxiety scales, and only realise how bad they had been feeling after they have retired (Spelten et al, 1993). It seems probable that a similar habituation would take place for their feelings of fatigue, such that a given score for a shift worker might reflect a far higher level of fatigue than a similar score from a non-shift worker. In short, it would appear that the majority of the increased risk of occupational accidents on abnormal work schedules stems from chronic effects rather than from the acute effects that form the bases of the current biomathematical models.

4.3 Individual Variability

A major limitation of biomathematical fatigue models is that they have typically been based on averaged fatigue ratings and other measures obtained from a limited number of individuals. Indeed, in many cases these individuals have been university students or military personnel and it is unclear whether their results can validly be generalised to other populations. In their defence, some of the models provide confidence intervals associated with each predicted value, allowing an estimation of the likely range across individuals. However, individuals clearly differ from one another on an enormously wide range of factors, many of which may impact on their fatigue and safety performance levels.

Di Milia et al (2011) reviewed the association between a wide range of demographic factors and the risk of involvement in road accidents. It should be noted that is far easier to examine the impact of various factors on road accidents, simply because they are so frequent, than it is in 'high reliability' domains such as commercial aviation. The authors nonetheless identified a number of dimensions of individual difference that were important in determining road accident risk, namely: *age, gender, socio-economic status, educational level, marital status, race and ethnicity, personality, circadian chronotype*[5]*,* and *'accident proneness'*. Some of the current biomathematical models can take account of the single dimension of circadian chronotype, but none of them can take account of the range of other dimensions covered in this research. Indeed, the only dimension of chronotype that most of the models can take account of is that of morningness-eveningness (Horne & Östberg, 1976; predisposition to be a 'morning-person' or an 'evening-person'), and there is, for example, virtually no evidence that this relates to adjustment to circadian disruption or 'jet-lag' (see review by Adan et al, 2012).

There are also a wide range of individual health problems, including, but not confined to, sleep disorders, that may impact on fatigue and safety. Smolensky et al (2011) have recently reviewed these problems, again in relation to road accidents. They identified five types of sleep disorder that could impact on fatigue and safety, namely: *Insomnia, Narcolepsy, Obstructive sleep apnoea syndrome* (more commonly known as sleep apnoea), *Periodic limb movement disorder,* and *Restless legs syndrome*. However, they also listed a vast number of physical and mental health complaints, ranging from allergic and non-allergic rhinitis through clinical depression to rheumatoid arthritis, that could potentially compromise sleep and/or elevate daytime feelings of fatigue. Finally it is clear that a wide range of other factors pertaining to the individual may influence the quality and duration of their sleep. These include such diverse factors as being woken by young children, having a long commute to and from work, having a second job or strenuous or time-consuming pastime, or suffering from life stresses due to issues such as bereavement, house moving or divorce.

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[5] Circadian chronotype (typically referred to simply as 'chronotype') is an attribute reflecting the time of day that a person's physical functions (hormone level, body temperature, cognitive faculties, eating and sleeping patterns) are active, change or reach a certain level. The most commonly recognised aspect of this phenomenon relates to an individual's predisposition to be either a 'morning person' (one who prefers to wake up early and is more alert in the early part of the day) or an 'evening person' (one who is more alert in the late evening hours and prefers going to bed late).

In short, there are a number of reasons why current biomathematical models of fatigue may fail to predict safety outcomes. The majority fail to take account of the fact that the peak of the circadian rhythm in the risk of accidents and injuries occurs rather earlier than that in fatigue. They all also fail to model the chronic components of fatigue and risk, which would now appear to account for a large majority of the increased risk of accidents and injuries associated with abnormal work schedules. This chronic component will reflect on a large number of factors including deterioration in health associated with abnormal work schedules and a wide range of individual factors.

5 Model Applications

This section discusses a range of potential applications and uses of biomathematical fatigue models within the air carrier environment.

5.1 Forward Scheduling

A primary application of biomathematical fatigue models is to assist in crew scheduling and crew rostering practices. Biomathematical models of human fatigue provide a means of incorporating aspects of fatigue science into scheduling to reduce fatigue-related risk.

An important application of biomathematical fatigue models is to assist with developing optimal crew schedules (Gundel et al, 2007). By predicting times at which performance should be optimal, identifying timeframes where restorative sleep will be maximised, and determining the impact of proposed work/rest schedules on overall fatigue and performance, models can be used to assist in the development of work schedules that reduce fatigue-related risk (Caldwell et al, 2009; Civil Aviation Safety Authority, 2010).

When applying biomathematical fatigue models for scheduling purposes, it is important to recognise the limitations of their use, as discussed in Section 2. In particular, it is essential to avoid overly simplistic interpretations of fatigue scores, and to recognise that any specified upper limits for fatigue scores must be validated within the operational environment in which they will be used.

Within the context of scheduling, biomathematical fatigue models can be put to various uses, as described below.

a) Comparisons of work schedules

   Biomathematical fatigue models are particularly well suited for performing comparisons of alternative work schedules because the strongest scientific basis of fatigue models is that they capture important fatigue trends, rather than predicting absolute values of error or accident probabilities. The models typically provide an estimate of fatigue risk over time, which may be examined to identify periods of high risk and to compare and evaluate different scheduling options (Rangan & Van Dongen, 2013). Schedules can then be varied to optimise different criteria to maximise overall efficiency while reducing risk exposure due to fatigue. In aviation, the determination of optimal departure time and layover length for the scheduling of Ultra Long Range flight operations has demonstrated the usefulness of biomathematical models for this purpose (Spencer & Robertson, 2007).

   Schedule comparisons can be performed for both future planned schedules (forward scheduling) and to assess the changes in fatigue risk relating to non-scheduled or irregular operations, such as those resulting from unforeseen operational requirements and/or unplanned shift changes. This may involve dynamic monitoring of rosters to alert schedulers to elevated fatigue risks associated with proposed or enforced changes.

b) Identification of vulnerabilities within schedules

   Models can also be used to identify high-risk fatigue vulnerabilities within existing flight crew schedules to provide a focus for mitigation strategies. Given a roster with fixed flight times, predictions of fatigue risk can highlight operational periods where elevated fatigue levels may coincide with critical tasks. Mitigation strategies for crew members may then be encouraged to assist with the management of these high risk periods, including, crew augmentation, extra rest time, strategic caffeine consumption or other risk management actions (Civil Aviation Safety Authority, 2010; Dean et al, 2004).

c) Evaluation of rosters that extend beyond prescriptive limits

Biomathematical fatigue models, as part of a holistic FRMS, can also contribute to fatigue risk assessments during the design of schedules and fatigue mitigation strategies for crew rosters that extend working hours beyond prescriptive Flight and Duty Time Limitations (FTL), or to evaluate the impact of reducing crew rest periods (Cabon et al, 2012). Specifically, biomathematical fatigue models can help evaluate the safety risk of a flight schedule or crew roster that falls outside of prescriptive FTL against a scientifically based standard. In such cases, the data from models should be supplemented with operational validation data to further support and justify this evaluation. One approach may include comparing predicted risk scores of newly considered rosters against benchmark risk scores of rosters with good safety records (e.g., certain long range flights), provided suitable benchmark rosters can be identified, using the same relative comparison strategy described in the previous point. This determination may be used, in conjunction with other fatigue risk management strategies, to inform fatigue risk assessments of alternative work schedules (Civil Aviation Safety Authority, 2010). This particular application may be of use to both aviation schedulers, and to regulators in assessing the suitability of newly proposed roster patterns.

d) Optimising crew pairings and bid lines[6]

Some biomathematical models have the capacity to incorporate instant fatigue risk assessments during schedule building to evaluate different crew pairing options. Pairing options can then be evaluated and compared to select those that avoid excessive fatigue risk. Similarly, some models can assist with decisions regarding bid lines by comparing and evaluating different scheduling options.

5.2 Non-scheduled / Irregular Operations

In addition to assisting with various aspects of forward scheduling, biomathematical fatigue models can also be applied to evaluate fatigue risks associated with unplanned changes to operating requirements and/or original crew rosters.

5.3 Work / Rest Cycles in Augmented Crew

Biomathematical fatigue models may be used to determine the optimal work / rest cycles for augmented flight crew operations, where the scheduled flight duty period can be extended through the deployment of additional crew members, allowing all crew the opportunity to obtain scheduled in-flight rest.

5.4 Light Exposure and Napping Countermeasures

Another potential application of biomathematical fatigue models is to evaluate the opportunity for countermeasures such as light exposure, at-home sleep timing or napping to reduce the effects of fatigue (Mallis et al, 2004; Dean et al, 2007). Exploratory scenarios may be evaluated through biomathematical fatigue models to test the potential impact of various countermeasures on fatigue risk and provide guidance on which countermeasures to implement, and when to use them (Civil Aviation Safety Authority, 2010).

Decisions regarding the appropriateness of various countermeasures must take into account their operational objectives. For instance, in applications requiring a high level performance at certain critical times, countermeasures will be aimed at maximising performance at those

[6] Bid lines are a sequence of flight crew roster pairings that are pre-built into ‘legal’ patterns by a computer program, usually on a monthly or two-monthly basis, then made available for bidding (requesting of that bid line / duty schedule) by flight crew.

times, whereas applications designed to reduce fatigue risk through napping may be aimed at optimising the timing of napping opportunities. The intended operational objectives of fatigue countermeasures may therefore vary depending on the type of schedule involved (Dean et al, 2007).

The evaluation of countermeasures using biomathematical models may be performed for several purposes. One is to improve work schedules that, without countermeasures, may result in degraded alertness or performance during scheduled work times (Dean et al, 2007). The capacity of such models to predict fluctuations in worker alertness and performance is key to determining the optimal times to apply countermeasures to prevent performance-impairing fatigue (Mallis et al, 2004).

Another purpose is to enable appropriate countermeasures, such as those relating to in-flight napping (Controlled Rest on the Flight Deck) or light exposure, to be integrated into operational procedures or guidance material. Organisations can use the results of evaluations of countermeasure effectiveness to guide organisational decisions about countermeasure implementation (Dean et al, 2007). For instance, the use of a biomathematical model (SAFE) was seen as very useful to determine the optimal rest distribution and timing among crews in Ultra Long Range (ULR) flights (Robertson et al, 1997; Spencer & Robertson, 2007).

Evaluations of countermeasure effectiveness can also be used to complement educational material for crew, by providing insight into how the implementation of fatigue countermeasures of different types and at different times affects overall fatigue risk. The results of such analyses can be used to educate crew on how to optimise and manage fatigue risk mitigation strategies (Dawson et al, 2011).

5.5 Individual Fatigue Prediction

The effects of sleep loss vary considerably among individuals. A potential application of fatigue models would be to provide guidance to individual crew members on their expected level of fatigue at a given time. This information could be used to improve sleep management strategies and to apply personalised fatigue countermeasures. Unfortunately however, currently available biomathematical fatigue models tend to be based on averaged fatigue ratings and are restricted therefore to predicting risk probabilities for a target population average rather than the instantaneous fatigue levels of a specific individual. However, related research has demonstrated that the 3-process model (integrated into the SWP, which is also the scientific basis of the BAM) has quite high accuracy in predicting individual sleepiness and sleep timing (Åkerstedt et al, 2007).

Recent technological developments have also seen the emergence of a range of applications (apps) for use with rapidly evolving ‘smartphone’ technology. Broader research has included the development of smartphone apps for monitoring motor vehicle driver alertness and distraction that issue warnings to drivers if their safety is compromised (Lee & Chung, 2012; You et al, 2013), and for both predicting sleep quality (Bai et al, 2012) and monitoring sleep quality (Hao et al, 2013) via the use of embedded mobile phone technology. Similar developments are underway for the aviation domain, with one of the selected models having already developed and released quite a sophisticated alertness and fatigue management app for use across *iOS* platforms by professional flight crew (see Persson & Andersson, 2013).

While the currently available app is able to take account of a range of individual and contextual input variables, and this technology and similar applications will continue to evolve and be developed, it should be noted that such tools are intended as an aid to predict alertness for an “average” individual, under “typical” conditions.

As noted above, none of the available biomathematical models are equipped to take into account all of the numerous individual factors that may impact on fatigue, such as age, gender, lifestyle, health status and personality traits. Some of the models do, nevertheless, have the capacity to allow their outputs to be tailored to some degree to the specific characteristics of the individual by incorporating individual traits or characteristics as optional inputs. One such input is the inclusion of circadian chronotype in some models (see Adan et al, 2012). Other inputs such as individual sleep need, habitual sleep timing, and commuting time can also be incorporated into some models, with the aim of providing fatigue predictions with greater accuracy than generic population average predictions.

Where knowledge of a specific individual's fatigue state is desired, other tools for direct assessment of fatigue state, such as neurobehavioral tests, may eventually be a solution. Continued development of fatigue model individualisation approaches may contribute to enhanced individual fatigue prediction in the future (Civil Aviation Safety Authority, 2010). For example, if fatigue or task error measurements and sleep monitoring data were available for specific individuals, then programs for providing individualised fatigue predictions (Van Dongen et al, 2007) could be used for a variety of applications, including on-line fatigue monitoring and as an educational tool to help individuals develop mitigation strategies that work uniquely for them. These types of 'individualised' programs may improve predictions for individuals, but the same caveat applies, that they are only one estimate of the probability of fatigue, not an absolute measure of fatigue risk.

5.6 Training

A key focus in managing fatigue risk in operational contexts is education, specifically, education about the effects of fatigue, the causes of fatigue, the importance of effective sleep and good sleep habits, and the appropriate use of fatigue countermeasures (Caldwell et al, 2009). Caldwell et al (2009) argue that all aviation industry personnel, including supervisors, crewmembers and scheduling staff, should be provided with education on these topics under an effective Fatigue Risk Management System (FRMS). They argue, for instance, that a detailed understanding on the importance of quality pre-duty sleep, on the effective utilisation of available sleep opportunities, on the use of napping for “bridging the gap between consolidated sleep episodes”, on appropriate nap timings, and on the effects of time zone changes, for instance, can be valuable in assisting crew to manage fatigue (Caldwell et al, 2009).

Biomathematical fatigue models can be used to provide fatigue risk management education of this sort, both for decision makers and for front-line workers. Understanding the latest scientific knowledge about the effects of sleep and circadian factors on fatigue can be difficult for operational personnel to absorb from scientific documents. Computerised implementations of biomathematical fatigue models that allow users to interactively observe changes in fatigue predictions through a dynamic user interface can form a useful component in a fatigue risk management educational program (Civil Aviation Safety Authority, 2010).

By demonstrating how variations in sleep duration, sleep times, nap timing and duration and other fatigue countermeasures alter fatigue risk, biomathematical fatigue models can be used to educate people on the dynamics of the sleep regulatory system and its effects on fatigue (Civil Aviation Safety Authority, 2010; Dawson et al, 2011). Dawson et al (2011, p. 551) suggest that the changes in fatigue risk over time may be counter-intuitive and that developing a better understanding of the “dynamics of the sleep-wake system” and how it affects fatigue can assist in the identification of periods of elevated fatigue risk and in planning and managing strategies to mitigate the risks. This knowledge is useful both for crew themselves, so that they may adapt their lifestyle and behaviours accordingly, and for the schedulers and decision makers responsible for reducing fatigue-related risks to organisations.

5.7 Safety Investigation

Well before the development of the first biomathematical models, an early attempt to calculate fatigue risk was applied by NASA experts assisting in the investigation of the August 1993 AIA Flight 808 Controlled Flight Into Terrain (CFIT) accident at Guantanamo Bay, Cuba (National Transportation Safety Board, 1994; Rosekind et al, 1994). The NTSB investigation determined that the probable causes of this CFIT accident included “the impaired judgement, decision-making, and flying abilities of the captain and flight crew due to the effects of fatigue…” (National Transportation Safety Board, 1994, p. v).

Additional factors cited as contributing to the Guantanamo Bay accident were the inadequacy of the flight and duty time regulations applied to *14 CFR, Part 121, Supplemental Air Carrier, International Operations*, and the circumstances that resulted in the extended flight/duty hours and fatigue of the flight crew.

To evaluate the contribution of fatigue to this accident, the cumulative sleep/wake debt was computed for the three crewmembers by using a simple ratio of wake/sleep, which was then compared to a usual baseline. Since that time, probable fatigue risk levels have been calculated for crewmembers involved in numerous aviation incidents and accidents, and in recent years biomathematical models have been employed by both operators and investigation agencies to assist with these calculations.

Several biomathematical models claim to be useful for supporting incident/accident investigation by assessing the potential contribution of schedule-related fatigue to safety events (e.g., FAID) or analysing a person's fatigue level at a specific time based on analysis of their prior sleep (e.g., SAFE). It is important to note, however, that the application of such models for the post hoc identification and analysis of the role of fatigue as a contributing factor to aviation incidents and accidents should be undertaken with great caution. While many authors (eg., Folkard & Åkerstedt, 2004; Hobbs & Williamson, 2003; Lenne et al, 1997; Mitler, et al, 1988; Williamson et al, 2011) have drawn links between fatigue and safety events in various occupational settings, it is extremely difficult to *prove* that a safety occurrence was contributed to by fatigue. While the potential for fatigue and its effects to be present can be noted, a causal relationship is extremely difficult to establish.

Contemporary systemic thinking on safety investigation and analysis recognises that complex interactions between numerous factors contribute to most safety occurrences. While it may be possible to identify the potential for the existence of crew fatigue and related performance decrements using such models after an event, establishing a definitive evidence-based link between fatigue and a specific event is problematic. Isolating fatigue from the numerous other factors that may have contributed to an event, then proving its contribution may not be possible. Validating this potential application of biomathematical models is also particularly difficult in the aviation domain, where accident rates are generally low, and it can be otherwise difficult, time consuming and expensive to measure the in situ performance of operational personnel (for example, using LOSA [Line Operations Safety Audit; see Federal Aviation Administration, 2006; International Civil Aviation Organization, 2002] or similar observational methods).

6 Model Characteristics and Structure

This section explains the nature of biomathematical models of fatigue, in terms of their internal structures and formulae (‘components’), the variables that can be entered into the models (‘inputs’), and the prediction measures or outcomes that are produced (‘outputs’).[7]

6.1 Model Components

The internal components of fatigue models are the characteristics of human neurobehavioral physiology that are described by the biomathematical equations in the model. The following characteristics may be included.

Homeostatic sleep drive

Fatigue and the need for sleep vary according to the amount of time a person has been awake and asleep. The homeostatic process (known as process sleep [S]) models this relationship. Obtaining inadequate amounts of sleep relative to individual sleep need leads to detectable deficits in alertness. These deficits manifest in a dose dependent manner (i.e., the more sleep is restricted, the worse the level of deficit) and are modulated by a 24-hour fluctuation in alertness associated with a circadian process. Models of the homeostatic process have demonstrated predictive accuracy in explaining fatigue resulting from continuous extended wakefulness (total sleep deprivation). More recent data has shown that when a person experiences chronic sleep restriction (restricted sleep across a period of days), more sleep time than previously predicted is needed to restore alertness to baseline levels Some biomathematical models have the capacity to account for the accumulation of longer-term 'chronic' impairment and recovery on an “ad hoc” basis, but there has been very little scientific research on this and it remains, an area of scientific uncertainty.

Circadian processes

The circadian process (process C) is governed by an internal biological clock with a period of approximately 24 hours (circadian pacemaker) that decreases levels of fatigue and sleep propensity during habitual day, and increases fatigue and sleep propensity during habitual night. This process operates independently of the time awake (modelled by the homeostatic process). Desynchronisation of the internal circadian pacemaker from habitual waking and sleeping hours contributes to the increased fatigue risk of irregular shifts or jet lag conditions.

Sleep inertia

Sleep inertia (or process Waking [W]) refers to the experience of temporary disorientation, grogginess and performance impairment that can occur as the brain progresses through the process of waking up. Sleep inertia decreases performance and alertness, and increases sleep propensity transiently after waking. Its effects are most severe immediately after waking from deep sleep and can last for as long as two hours (Jewett et al, 1999).

Circadian phase adaptation

The circadian clock aligns itself to external cues such as the timing of light/dark cycles (e.g. sunrise/sunset). Disrupting the timing of these cues by travelling across time zones (jet lag) or working at night or on irregular schedules may result in a realignment of the circadian clock that needs to be modelled in the fatigue algorithms in order to generate accurate predictions. Individuals alter their light exposure by the choices they make about when to sleep and go outside, for instance. In the long haul aviation context, behaviour during layovers is likely to be an important factor affecting adaptation in different time zones and there is limited data

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7 Some of the definitions and descriptions in this section have been adapted from the previous version of this report (Civil Aviation Safety Authority, 2010).

available on this. Some circadian models adapt the phase of the circadian clock by using light exposure and timing as inputs, whereas others use rules based on magnitude of the time-zone shift to produce a circadian adjustment. Because few studies have tracked the circadian rhythms of crewmembers during flight operations, the rate of adaptation of an individual's circadian clock after time-zone shifts is another area of scientific uncertainty, especially since there are likely to be large individual differences in this respect.

Work type

Some models include a work or job type component to account for the differences in fatigue accumulation associated with the nature, intensity and risk of the activity being undertaken. Work type may impact on the accuracy of fatigue estimates, and may also affect interpretation of fatigue risks. For instance, different fatigue levels may be deemed appropriate for cabin crew versus flight crew, or for flight crew undergoing training or simulator activities versus operational flying duties. Work type as a model component should be treated with caution, however, as there is minimal data on how different activities impact on fatigue or alertness. Furthermore, the effects of workload components have often been estimated from laboratory studies or studies of industrial shift workers and may thus have limited applicability to the diverse range of activities undertaken in the aviation industry.

Time on task

The time spent performing a task is another factor that is known to affect fatigue and performance, with greater fatigue associated with longer sustained efforts on a given task. The time-on-task related effects are worsened with increased sleep loss and are modulated by the circadian clock.

6.2 Model Inputs

The inputs to a biomathematical fatigue model are the variables that need to be provided to enable the model to determine output predictions. The quality of input data and availability of sources within an organisation to provide the data are two important considerations for selecting and utilising a fatigue model. The minimum information typically required for fatigue prediction includes work-rest schedule and/or sleep data.

Additional factors that may modulate the effects of hours of work on fatigue can be used to complement these essential inputs. These factors address aspects of individual variability and the type of activity (time zone, workload, etc.).

For the purposes of the evaluation of biomathematical fatigue models in this report, three types of inputs are considered:

- *Required inputs*, i.e., information that is essential to predict fatigue;
- *Work related inputs* that can increase prediction accuracy by taking into consideration some specific factors associated with the aviation context;
- *Individual inputs* that enable predictions to be moderated using information about a particular person's characteristics, referred to as *individualisation*.

6.2.1 Required Inputs

Actual sleep timing

The quantity and timing of actual sleep is the primary determining factor in predicting fatigue related to sleep deficit. There are three main methods to assess actual sleep timing:

- *Polysomnography* refers to the process of studying a person while asleep by taking comprehensive recordings of numerous physiological changes (brain waves, eye movements, muscular activity, etc.). The advantage of polysomnography is that it produces an in-depth analysis of sleep (including sleep stages). It is expensive and time-consuming however, requires expertise and is very intrusive. Although it has been used in some applied research in aviation (including in-flight sleep, Signal et al, 2005), it is more suited to research settings than to operational fatigue management.

- *Actigraphy* involves measuring the physical activity of an individual over several days or weeks, typically using a wrist-worn accelerometer (an actiwatch). This provides a motion signal from which manual or computerised analysis can estimate wake and sleep periods reliably. Actigraphy is an objective, non-intrusive and valid measure of sleep quantity and timing, which can also provide an estimate of sleep quality. Actigraphy is now widely used by operators to support specific studies in the context of FRMS.

- A *sleep diary* or sleep log is a record of an individual's sleeping and waking times, typically made over a period of several weeks. It is an inexpensive technique and provides a subjective estimate of sleep quantity and quality. Several types of sleep diary exist and include information such as daily activities, nutrition and subjective fatigue. In most applied research, actigraphy and sleep diary data are collected in parallel. Depending on the available resources, sleep diaries can be used alone to provide a measure of sleep timings, although the accuracy of self-reported sleep data may be limited. For example, a recent study (Lauderdale et al, 2009) found a poor correlation between reported and measured sleep durations (with persons sleeping five and seven hours over-reporting, on average by 1.3 (26%) and 0.3 (4%) hours respectively).

Work schedule

Biomathematical models use work schedules to estimate fatigue or performance metrics and/or sleep periods that are likely to occur between on-duty shifts. Although work schedule has the advantage of being a data source that is directly available as part of operational crew scheduling, it provides a less accurate estimate of actual sleep obtained than the direct measurement options described above.

6.2.2 Work Related Inputs

Time zone changes (>3)

It is well established that the effects of time zone changes on circadian processes are significant after the crossing of 3 or more time zones (Samel et al, 1995). During a prolonged stay (at least 48 hours) in the new location after a time zone change, the biological clock starts to adjust to the local time with a speed that may vary among individuals. The direction of the time zone transition impacts the speed of adjustment, with an eastward transition leading to a slower adjustment than a westward journey. This transition (also called acclimatisation) produces the so-called ‘jet lag’ syndrome (characterised by sleep disturbances, fatigue and performance decrements). The ability to input data on time zone changes is thus an important feature of a biomathematical model, particularly where the conduct and evaluation of transmeridian flights across multiple time zones is an essential requirement.

Crew composition

The crew composition (number of crew members deployed) is an important input to consider for extended duty time operations (augmented flights).

In-flight rest facilities (bunk or seats)

Scientific research has shown that the type of in-flight rest facility provided significantly impacts on sleep quantity and quality. The ability of a model to input the type of in-flight rest facility is therefore useful in the case of augmented crew flight evaluations.

Take off and landing waypoints

Take off and landing waypoints are required inputs for some models. In some cases, these are used to derive the number of sectors flown, which, as noted below, can be an important consideration in relation to fatigue. In other cases, these are used to calculate time zone transitions.

Multiple sectors

The number of sectors flown is an important factor to consider, especially when evaluating multi-sector operations (e.g., regional/domestic airline operations, charter, tourism and agricultural flights, emergency medical services, etc.), as the number of sectors operated has been shown to affect fatigue level. Some models may infer number of sectors from the take off and landing waypoints provided, while others allow number of sectors to be added as an independent input.

Workload

This refers to the workload or attention required by the type of task being undertaken. Little is known about the effects of these factors on fatigue, and few models offer the capability to input measures of factors such as workload, attentional requirements or stress. These factors could be potentially useful however in reflecting the workload variations of flight and cabin crew over different flight phases. It should be noted that the link between workload and its effect on fatigue is complex, and caution should be used if attempting to include it as an input.

6.2.3 Individualisation

Fatigue predictions from biomathematical models are based on the alertness of the ‘average’ person. There is considerable variability between individuals in the amount of sleep habitually needed and in vulnerability to impairment due to sleep loss (Van Dongen, 2004). Alertness predictions for individuals can thus be improved by adjusting the models to incorporate specific information about the characteristics of the particular person. It should be remembered, however, that while inclusion of these individualised inputs may provide greater refinements to predictions, the outputs are still generated on the basis of population averages and so are unable to provide an accurate reflection of an individual’s fatigue.

Habitual sleep duration

Habitual sleep duration, or a person’s individual need for sleep, is one of two important sources of individual variability in the response to hours of work (the other, chronotype, is discussed below). The customary required sleep duration varies among individuals from five hours (short sleepers) to 10 hours (long sleepers) with most people requiring between seven and eight hours of sleep per night.

Chronotype

Chronotype refers to a person’s tendency to be a ‘morning type’ or ‘evening type’. This can be determined based on the individual’s sleep–wake cycle or with a standardised survey such as the Morningness–Eveningness Questionnaire (MEQ, Horne & Östberg, 1976) or, more recently, the Munich Chronotype Questionnaire (Roenneberg et al, 2003; Zavada et al, 2005). Only a few models allow the input of individual chronotype. It would be unrealistic to build customised hours of work models based on a particular worker’s chronotype, but where models can accommodate chronotype, a conservative strategy could be to run a prediction using the least favourable profile, e.g., evaluating a morning shift with an evening type profile.

Commuting

Crewmembers often live far away from the base where they are required to report for duty. This necessitates long commute times both before and after work periods. Long commuting times have obvious effects on fatigue as they reduce sleep opportunities. Some models allow for the input of specific commuting times to account for these variations.

6.3 Model Outputs

The outputs (or metrics) of a biomathematical fatigue model reflect the input data and calculations involved. While the primary aim of most of the models selected is to predict fatigue, several additional metrics have been added and therefore most models are able to provide a range of outputs. The common types of model outputs are explained below.

Subjective alertness

Most of the biomathematical models provide a fatigue or alertness prediction value over a given work period. These values are generally expressed on a subjective scale. As discussed above, the most commonly used scales in aviation are the *Karolinska Sleepiness Scale (KSS)* and the *Samn Perelli (SP)* fatigue scale. The KSS has been validated against objective measurement of sleepiness and performance evaluation and the SP scale has been validated and widely used in aviation.

Estimated sleep / wake times

Models that accept work times or scheduled sleep opportunities as inputs may estimate sleep/wake times as an intermediate variable that can be provided as an output. The duration of sleep obtained during a sleep opportunity window is affected by numerous factors, including a biological sleep propensity that is determined in part by homeostatic and circadian states. There are ‘circadian forbidden zones’ during the day when initiating sleep is difficult, especially when combined with a low homeostatic sleep drive. In addition to their use in predicting fatigue, estimations of timing and duration of sleep can be utilised to develop biologically compatible schedules.

Performance

Because of the inherent limitations of subjective alertness or fatigue measures, several models provide metrics more adapted to the real world such as cognitive effectiveness measured on a reaction time test (e.g., the percent change in cognitive speed, lapse likelihood, reaction time). An important limitation of this approach is that performance tests are only limited 'part-tasks' that do not capture all the skill dimensions required for safe operation of complex equipment such as aircraft. In addition, this form of performance testing measures the status (and compliance) of an individual crewmember, not the functional capacity of a multi-person crew.

Fatigue-related task errors

The probability of a fatigue-related task error is a type of model output that has relevance to a particular operational environment. Objective assessments of fatigue-related task errors can be accomplished by measuring the operational task directly. Often the task does not lend itself to measurement and so performance measures are embedded into the task (e.g., glideslope deviations, optimal use of thrust, etc.).

Fatigue-related risk of operational accidents

Predictions of fatigue-related contribution to the risk of an operational accident causing loss of human life or financial costs would be the most easily interpreted model output for use in an FRMS. This type of prediction is different from fatigue-related task errors, as most aviation systems are built with safety factors and layers of redundancy that provide a degree of tolerance to human error. Fatigue-related operational incidents and accidents usually involve an unfortunate combination of multiple contributors and occur with a very low base rate, as discussed in Section 4.1. Accident risk metrics assign a relative probability about the presence of fatigue related risk factors for an operational accident, but developing such models is especially difficult in the aviation industry given the low base rates of accidents.

Confidence intervals

Model predictions typically represent estimated average fatigue or risk levels. Actual levels can vary from this mean, and confidence intervals are used to represent the range of values that can be expected as part of the random variation.

7 Selected Biomathematical Fatigue Models

This section of the report is designed to provide potential users with an up-to-date summary of each model. The information includes an overview of each model, a brief description of its objective and main applications, and a summary of the model outputs, validation processes, advantages and limitations. Relevant references are listed at the end of each model description.

All of the information in this section is based on published research, and publicly available brochures and guidance material relating to the various models (see the Reference list for details). Further details were obtained through personal correspondence with contacts from the relevant organisations, who also completed a structured survey asking them to confirm and / or add information. Some of the information provided has been transcribed directly in the tables without specific attribution. The organisations have been given an opportunity to review and correct any details relating to their models, and their feedback has been incorporated. Nevertheless, this information should be treated as indicative only and may be subject to change.

No independent verification of claims has been conducted. As recommended in the previous version of this report (Civil Aviation Safety Authority, 2010), users should ensure that they are provided with written information regarding the dimensions of fatigue that are considered by the model, the mechanisms by which they are considered, data sets used to validate the model, and the cautions and limitations that should apply to interpretation of outputs. Model developers or distributors should discharge their duty of care to ensure that this information is comprehensive, accurate and does not overstate model capabilities.

7.1 Summary of Each Model

The tables in this section provide key details, in alphabetical order, for each of the biomathematical fatigue models considered in this review:

Boeing Alertness Model (BAM)

Model	Boeing Alertness Model (BAM)
Version	2.0
Institution	Jeppesen: www.jeppesen.com
Contact	Tomas Klemets Head of Scheduling Safety, Jeppesen tomas.klemets@jeppesen.com
Description of the Model	The Boeing Alertness Model (BAM) is a biomathematical model of alertness, built on the Three Process Model of Alertness and extended with advanced sleep prediction, task load, augmentation, and ability to blend in sections of actual sleep/wake when available. BAM has an associated iPhone / iPad application, CrewAlert.
Objective	BAM is built to support the complex crew management processes for airlines of all sizes.
Main Applications	BAM can be used for post-analysis of crew schedules (pairing and rosters) but also together with pairing and roster optimisers during the construction phase. The ability to run with optimisers also enables running what-ifs to evolve the flight and duty time limit rules under an FRMS.
Outputs	The output of the model is sleepiness on the KSS scale, converted into a proposed common scale for prediction models that returns an alertness score from 0 to 10,000.
Cost	BAM is available in several different ways and the cost depends on the usage and the support level required. BAM is available free of charge world-wide through the iPhone / iPad app CrewAlert Lite but also in paid versions for integration with crew planning systems.
Support and Training	BAM is supported from Jeppesen offices in Denver, Gothenburg and Singapore. Support is available on two levels: office hours or 24/7. Training courses are offered in Denver, Montreal, Gothenburg and Singapore. User guides and written tutorials are available for CrewAlert and for integrated use with crew management solutions.
Data set used to develop the model	BAM implements the Three Process Model of alertness and therefore largely relies on the data behind that development. Sleep prediction and task load has been developed further, driven by collected data from airline operations.
Validation	To date, Boeing / Jeppesen have undertaken four large-scale data collections from airline crew, to validate and enhance BAM to best reflect actual operation. This data, together with data shared by airlines, makes up close to 60,000 assessments from actual airline operations.
Advantages	• Fast enough to be integrated with industry-strength optimisers *during* crew scheduling construction (rather than measuring rosters after construction). • Suitable for large-scale application, and can be integrated with crew planning tools used by airlines. BAM enables up to 256,000 flights to be predicted per second on a modern CPU, scaling further via multi-core execution. • Enhanced through a data-driven continuous improvement methodology. • Individual fatigue monitoring and large scale data gathering are possible through the iPhone / iPad application, CrewAlert. • The CrewAlert application can be used for visualising scheduling patterns in small operations and evaluating options. • The CrewAlert application can also be used by crewmembers to visualise the impact of planned schedules on future alertness. • The model has a built-in ability to produce fatigue mitigation strategies for a given time with an output of sleep/wake patterns and timings for light exposure. • Designed for aviation applications. • A limited version of BAM is available free of charge via the CrewAlert Lite iPhone/ / iPad application.

Limitations	• Cost may be a consideration for some organisations. • Predictions are based on population averages (as with other models).
Relevant Publications	Jeppesen. (2009). *Fatigue Risk Management*. Available from: http://ww1.jeppesen.com/documents/aviation/pdfs/Fatigue_2009-10_Final_II.pdf Jeppesen. (2014). *Jeppesen Fatigue Risk Management Portfolio*. Available from: http://ww1.jeppesen.com/industry-solutions/aviation/commercial/fatigue-risk-management.jsp (This page provides an overview of Jeppesen FRM products and services). Jeppesen. (2011). *Technical Fact Sheet: The Boeing Alertness Model.* Available from: http://ww1.jeppesen.com/documents/aviation/commercial/BAM_IV.pdf Klemets, T. (2011). *Analysis of FRMS Forum data using the Boeing Alertness Model (BAM)*. Available from: http://www.frmsforum.org/cms_media/files/bam_klemets_final.pdf?static=1 Olbert, A., Hellerstrom, D., & Klemets, T. (2011). *A comprehensive investigation of flight and duty time limitations and their ability to control crew fatigue.* Available from: http://ww1.jeppesen.com/documents/aviation/commercial/GPA_white_paper.pdf Persson, A., & Anderson, J. (2013). *Mobile applications design in fatigue risk management*. Masters thesis, Chalmers University of Technology, Gothenburg, Sweden.

Circadian Alertness Simulator (CAS)

Model	Circadian Alertness Simulator (CAS)
Version	CAS-5
Institution	Circadian: www.circadian.com
Contact	Rainer Guttkuhn Technical Manager, Circadian rguttkuhn@circadian.com
Description of the Model	CAS is a bio-mathematical fatigue model that estimates fatigue risk of an individual's sleep-wake-work pattern in combination with a variety of individual-specific settings. The latest release of CAS (CAS-5) is specially optimised for crew planning and other airline FRMS applications.
Objective	The objective of CAS is to estimate risk associated with work-rest-sleep sequences.
Main Applications	CAS-5 is specifically optimised for crew planning applications (including crew pairings, bid lines and bidding) and other airline FRMS applications (including FRMS planning, aircrew education and sleep planning, reserve policy design and evaluation, fatigue reports and incident investigation, aircrew fatigue research and FRMS audits).
Outputs	The CAS Model provides a summary Fatigue Risk Index between 0 (low fatigue) and 100 (high fatigue).
Cost	Contact supplier for cost details.
Support and Training	Training and support are available.
Data set used to develop the model	Work-rest-sleep data from employees in various transportation modes including railroad, trucking and maritime was used to develop the model.
Validation	The CAS Fatigue Risk Index has been validated in multiple diverse real world transportation operations and shown to be highly sensitive in predicting the risk of human errors / incidents and accidents. CAS has been progressively optimised over 20 years using large populations of equipment operators where sleep and alertness on duty has been simultaneously measured. CAS predictions have been validated through multiple investigations of the correlation between aircrew subjective alertness and CAS alertness metrics.
Advantages	• Suitable for large-scale application (batch processing has been done with data sets exceeding 10,000 individual employees) and integration with crew planning tools. • The latest version (CAS-5) is specifically optimised for crew planning and other airline FRMS applications. The specific fatigue risks of Commuter, Long-Haul, Ultra Long Range passenger, freight and corporate aviation operations are addressed by the model. • Applicable for use for pilot, flight attendant and ground crew groups.
Limitations	• Cost may be a consideration for some organisations. • Predictions are based on population averages (as with other models).
Relevant Publications	Circadian. (2014). *CAS (Circadian Alertness Simulator)*. Unpublished document. Circadian. (2012). *CAS-5: Fatigue risk module for crew planners*. Available from: http://www.circadian.com/247-industries/aviation/cas-5-fatigue-risk-model.html Moore-Ede, M. (2011). *Circadian Alertness Simulator CAS-5 Modeling of Aircrew Fatigue Risk* (presentation). Moore-Ede, M., Heitmann, A., Guttkuhn, R., Trutschel, U., Aguirre, A., & Croke, D. (2004). Circadian alertness simulator for fatigue risk assessment in transportation: Application to reduce frequency and severity of truck accidents. *Aviation, Space, and Environmental Medicine 75*(3), Section II, A107-118.

Fatigue Assessment Tool by InterDynamics (FAID)

Model	Fatigue Assessment Tool by InterDynamics (FAID)
Versions	FAID Standard v2.1 (v2.2 soon to be released), FAID AC (integrated with DFT8), FAID TZ (for personnel operating across multiple time zones), FAID Roster Tool (to support roster building and modification), FAID Roster Tool TZ, FAID / FAID TZ Shared Libraries (for integration within third party crew rostering and management software), and Business Wide versions (multi-level reporting and fully customised to the operator's requirements).
Institution	InterDynamics Pty Ltd: www.interdynamics.com (Intellectual property of the formulae and factors integrated into the FAID algorithm licenced from the Centre for Sleep Research, University of South Australia).
Contact	Tu Mushenko Senior Fatigue Risk Consultant, InterDynamics faid@interdynamics.com
Description of the Model	FAID Technologies are bio-mathematical models used to estimate fatigue exposure associated with hours of work. The FAID suite of decision support tools have been developed using scientific research and knowledge gained over several decades on circadian factors, the effects of shift lengths, timing of shifts, the importance of previous work periods on fatigue and performance, and applying key understandings of circadian phase adaption with time-zone travel. FAID Technology can be used to assess and manage the fatigue exposure of working hours to within Fatigue Tolerance Levels and Target Compliance percentages defined by the organisation.
Objective	FAID Technology aims to provide an indication of relative hours of work fatigue exposure associated with the planned or actual hours of work entered. Where task risk has been assigned to work schedule information, FAID Technology facilitates the management of working hours to within defined Fatigue Tolerance Levels and target Fatigue Tolerance Level compliance percentages, thereby limiting and auditing the fatigue exposure associated with the hours worked.
Main Applications	The primary application of FAID is the analysis of the fatigue exposure impacts of different work patterns, including time zone changes and various start and finish times, highlighting high risk times within shifts and supporting risk-based decisions. FAID technologies are customisable and address different operational environments and software implementations. FAID Roster Tool has been designed specifically to assist the building of rosters with immediate feedback.
Outputs	A FAID score indicates the likely sleep opportunity that a work-pattern allows. As the relative sleep opportunity associated with a work-pattern decreases, the FAID score increases. Main outputs include: Apparent Fatigue Tolerance Level (the score below which 98% of historical hours were worked); traffic-light coloured FAID Conditions representing increasing levels of risk; risk matrix view of individuals; graphical representation of risk against activity; tabular and graphical outputs; ranking shifts by Key Performance Indicator (KPI); filtered view of non-compliant work periods; annual KPI trends; staff utilisation reports; work pattern profiles.
Cost	Some FAID applications have published prices, while others are dependent on customisation and potential integration fees. In 2014, a single concurrent user licence for FAID Standard in Australia is AU$5,500 plus from the second year of use, annual licence access and support fees of AU$1,100 (all inclusive of GST). Price points can vary based on dataset limits or additional functionality.
Training and Support	InterDynamics provides tailored training to cater for the specific needs of an organisation and its personnel. Detailed User Guides are available. Payment of annual licence and support fees entitles organisations to upgrades to latest versions of FAID related software, technical support via e-mail or telephone and specialist technical support (including advice on importing roster data, minor application debugging and discussion on FAID usage and interpretation of FAID outputs).
Data set used to develop the model	The FAID algorithm has been validated in laboratory, simulator, and field based studies over more than a 10 year period. The earliest field-based validation study included 193 shift workers, whose work schedules reflected the range of possible conditions that could be expected in the

Data set used to develop the model…	Australian rail industry. The shift workers who participated in the study were train drivers from 5 of the 8 states and territories of Australia. All train drivers filled in daily sleep and work diaries, wore actigraphs, performed subjective alertness and objective performance tests, before and after each shift for a period of 2 weeks (Fletcher & Dawson 2001c).
Validation	The model has been validated using data from cumulative partial sleep deprivation, and continuous acute sleep deprivation (Fletcher, 1999). Validation studies have found psychomotor vigilance performance, subjective performance ratings, sleepiness and tiredness to all correlate soundly (Fletcher & Dawson, 2001a). Fletcher and Dawson (2001b) reviewed the model's prediction of changes in subjective and objective measures against data published from napping studies. Regression results indicated a strong to very strong relationship to logical reasoning, sleep latency scores, self-rated alertness, profile of mood state fatigue, visual vigilance, and reaction time. Rail studies have indicated a clear relationship between FAID scores, train driving performance (including safety metrics), psychomotor vigilance performance, and subjective alertness levels (Roach et al, 2001; Dorrian et al, 2007). Other validation work has included studies in aviation. One study of pilot performance and shift schedules (Stewart & Abboud,, 2005) found that FAID provided a useful means of predicting cumulative fatigue effects, with performance trends correlating soundly with FAID exposure indicators..
Advantages	• FAID Roster Tool offers the ability to manually build rosters across numerous groups or depots, to compare and store auditable planned and actual hours of work data and to see immediate feedback of FAID scores as shifts are allocated or added. • FAID is suitable for large-scale application. FAID Technology has been used to analyse datasets of over 7,000,000 work periods on a modern PC, and it can import schedules from spreadsheets and other sources. • Available to be an integrated component of crew rostering and management software via a shared library. • Has the ability to assess business wide hours of work fatigue exposures across multiple locations, workgroups, fleets, designations, etc. • Intra-shift displays of FAID Scores allow targeted risk mitigation strategies to be considered. • Provides KPIs from within a shift to across the workforce, with functionality supporting identification and review of individual shift patterns and broader systemic risk management. • The model and associated documentation seek to educate users on the limitations and appropriate use of the model, whilst offering practical fatigue risk management frameworks. • A range of versions with different functionality and data processing capabilities are available at varying price points. • A limited trial version is available at no cost.
Limitations	• Cost may be a consideration for some organisations, although limited versions are available for smaller operators at a reduced cost. • FAID versions do not take account of sleep inertia effects. • FAID is a model of fatigue exposure resulting from hours of work and, as such, mitigation strategies to reduce FAID scores are limited to changing work schedule timing and length. • Calculation of outputs is based on 'average' population data. This reduces the inputs required to known scheduled work hours, but means the model is less customisable to reflect personal characteristics of individuals. • Most aviation features are available only in FAID TZ and FAID Roster Tool TZ, not FAID Standard (e.g. augmented crew rest periods and sleep quality inputs, consideration of time zone and circadian phase adaptation factors). • Some considerations (such as number of sectors and commute times) can only be input indirectly by altering shift start/end times or separately entering each sector.

Relevant Publications	Dorrian, J., Hussey, F., & Dawson, D. (2007). Train driving efficiency and safety: examining the cost of fatigue, *Sleep Research*, *16*, 1-11. Fletcher, A. (1999). *Measurement and management of work-related fatigue: Development and preliminary validations of a predictive model*. Unpublished doctoral thesis, University of South Australia, Adelaide, Australia. Fletcher, A., & Dawson, D. (2001a). A quantitative model of work-related fatigue: empirical evaluations. *Ergonomics*, *44(5),* 475-488. Fletcher, A., & Dawson, D. (2001b). Evaluation of a fatigue model using data from published napping studies. *Journal of Human Ergology*, *30*, 279-285. Fletcher, A. & *Dawson*, D. (2001c). Field-based validations of a work-related fatigue model based on hours of work. *Transportation Research*, *Part F4*, 75-88. InterDynamics. (2014). *Fatigue risk management solutions: Facilitating practical, effective FRMS implementations and positive cultural change.* Available from: http://www.interdynamics.com/wp-content/uploads/2014/01/InterDynamicsFRMSolutions.pdf InterDynamics. (2014). *Related Peer Reviewed Papers and Books*. Available from: http://www.interdynamics.com/fatigue-risk-management-solutions/related-papers-and-books/ InterDynamics. (2014). *What you need to know about FAID*. Available from: http://www.interdynamics.com/wp-content/uploads/2014/01/WhatYouNeedToKnowAboutFAID.pdf Roach, G. D., Dorrian, J., Fletcher, A., & Dawson, D. (2001). Comparing the effects of fatigue and alcohol consumption on locomotive engineers' performance in a rail simulator, *Journal of Human Human Ergology*, *30 (1-2)*, 125-130. Stewart, S., & Abboud, R. (2005). Flight crew scheduling, performance, and fatigue in a UK airline - Phase 1. *Proceedings of Flight Management in Transportation Operations*, September 11-15, Seattle, USA.

Fatigue Risk Index (FRI)

Model	Fatigue Risk Index (FRI)
Version	FRI v2.3, January 2013
Institution	UK Health and Safety Executive: www.hse.gov.uk
Contacts	Mick Spencer (Fatigue Index): mickspencer@btopenworld.com Simon Folkard (Risk Index): S.Folkard@swansea.ac.uk
Description of the Model	The Fatigue and Risk Index (FRI) is designed primarily for comparing different work schedules, or for examining the potential impact of a change to one feature of a given work schedule (e.g. shift change-over times). It can also be used to identify the fatigue or risk associated with any particular shift within a given schedule that may be of concern. It is a revised and updated version of the HSE Fatigue Index (FI). Extensive changes were made to the previous version, incorporating recent information on issues including cumulative fatigue, time of day, shift length, the effect of breaks and the recovery from a sequence of shifts. An additional review was carried out of the trends in the risk of accidents and injuries related to different features of work schedules, which enabled the final version of the FRI to incorporate two separate indices, one related to fatigue (the Fatigue Index) and the other to risk (the Risk Index).
Objective	To compare different shift schedules on the probability of high levels of sleepiness (the Fatigue score), and on the relative risk of an error that might result in an accident/injury (the Risk score).
Main Applications	The main applications of the tool are in comparing work schedules, examining the impact of specific changes to work schedules, and identifying the fatigue risk associated with given shift schedules.
Outputs	The Fatigue Index is expressed in terms of the estimated average probability, multiplied by 100, of a value of seven or more on the KSS (a 9-point scale), and therefore takes a value between zero and 100. The KSS has been extensively validated, and high scores are known to be associated with a high frequency of microsleeps. The Risk Index is expressed in terms of an estimate of the relative risk of making an error that could contribute to an injury or accident. The two outputs are not simple transformations of one another, and hence the two predictions may differ substantially for some work schedules.
Cost	FRI is available for download for free from the UK Health and Safety Executive website: www.hse.gov.uk/research/rrhtm/rr446.htm
Training and Support	User guidance documentation is available.
Data set used to develop the model	The original data for developing the model was from shift workers in the rail industry and a wide range of other industrial settings. Further data was provided from aircrews, train drivers and from laboratory studies
Validation	Outputs from the model were validated against established trends in fatigue or risk in the literature for a variety of different work schedules. The cumulative and duty-timing components of the model were derived from empirical data obtained from studies of aircrew (Spencer & Robertson, 2000), train drivers (McGuffog et al, 2004), and, in the case of risk, trends in the occupational injuries and accidents of mainly industrial shift workers (Folkard & Lombardi, 2004). The job type/breaks component of the model was estimated from laboratory studies (Gillberg et al, 2003) and studies of industrial shift workers (Tucker et al, 2003). The Risk Index was also recently validated by independent research (Greubel & Nachreiner, 2013).
Advantages	• Available for immediate download and free for use. • Provides estimates of both fatigue and risk. • The model requires very few inputs in order to make fatigue predictions.
Limitations	• The model may overestimate the fatigue risk for individuals who show some circadian adjustment to their schedule, because the indices are based on rotating work schedules and assume that individuals will not show circadian adjustment to them.

Limitations…	• Predictions are based on population averages. • Suitable for performing shift comparisons, but is rather cumbersome when used for forward scheduling (e.g. building rosters). • Not designed specifically for aviation, and does not take many aviation-specific inputs into consideration (e.g. time zone changes, number of sectors flown) so may be more applicable for operations within a single time zone. • Aside from user guide documentation, no training or support is available for this model.
Relevant Publications	Folkard, S., Robertson, K., & Spencer, M. (2007). A fatigue/Risk Index to assess work schedules. *Somnologie, 11*, 177–185. Greubel, J., & Nachreiner, F. (2013). The validity of the risk index for comparing the accident risk associated with different work schedules. *Accident Analysis and Prevention, 50*: 1090-1095. Health and Safety Executive. (no date). *RR446 – The development of a fatigue / risk index for shiftworkers*. Available from: http://www.hse.gov.uk/research/rrhtm/rr446.htm (This site provides details of the model and links to the user guidance document and FRI spreadsheet). Spencer, M.B., Robertson, K.A., & Folkard, S. (2006). *The development of a fatigue / risk index for shiftworkers.* London: Health & Safety Executive.

System for Aircrew Fatigue Evaluation (SAFE)

Model	**System for Aircrew Fatigue Evaluation (SAFE)**
Version	SAFE v6.0
Institution	Fatigue Risk Management Science Ltd: www.frmsc.com
Contact	Douglas Mellor Director FRMSc Limited douglas.mellor@frmsc.com
Description of the Model	SAFE is a biomathematical model, commissioned by the UK Civil Aviation Authority as a regulatory tool assist with the assessment of likely fatigue in airline rosters. The underlying fatigue model was created from studies commissioned by the UK Ministry of Defence in 1980 and the UK CAA funded subsequent research for its application and use with aircrew. It is purpose built for the aviation industry. SAFE describes and predicts the likely fatigue and sleep patterns experienced by pilots for a given schedule of duties. It is validated for describing the fatigue experienced by commercial passenger jet pilots assigned to complete any given schedule of duties. The model is accessed through a secure connection to the Internet and is being integrated into a number of popular software packages such as AIMS (Airline Information Management System©) and FOS (Flight Operation System©). It can also be run on a client's server or personal computer. The current version of SAFE incorporates a Cabin crew Alertness & Rest Evaluation (CARE) model for predicting cabin crew fatigue.
Objective	The objective of SAFE is to evaluate the risks associated with particular duty schedules in the civil aviation industry.
Main Applications	The primary application of SAFE is to predict the fatigue experienced by aircrew for a given flight duty schedule.
Outputs	The outputs of the model are colour coded duty bars showing the development of fatigue during each duty in any schedule and associated sleep predictions. SAFE produces Samn Perelli (SP) fatigue scores (a 7-point scale) throughout the duty period (although options exist for other scales including Karolinska and 100 point alertness scales). A forecasted fatigue score is generated every 15 minutes and predicts likely sleep patterns.
Cost	The price of the model is dependent on the size of fleet and all users within an Air Operator's Certificate (AOC) are covered by the same license fee.
Training and Support	Fatigue Risk Management Science Ltd. can provide face-to-face or online training for all relevant groups, including schedulers. There is a tab on the model that contains an e-learning module for navigating SAFE along with some basic fatigue science, and a User Manual is also available. There is also a support line for users who need assistance.
Data set used to develop the model	The data set used to develop the basic sleep and fatigue model involved laboratory measurements of performance (reaction time, Digit symbol substitution, visuo-motor coordination) performed under protocols designed to examine the effects of time of day, time since sleep and time on task. The SAFE model was constructed using data collected from pilots working short-haul, long-haul, ultra long-haul and cargo operations from a number of international airlines. In addition to gathering subjective data on sleep and fatigue, reaction times and sleep patterns measured by actigraphs were collected. The onboard sleep part of the model was created using data from 3 and 4 crew operations in long-haul flights and 4 crew operations for ultra long haul flights. The data sets included EEG, actigraph data and subjective data when pilots slept in bunks or business class seats. The studies on aircrew enabled the effects of time of time zone changes on sleep and alertness and on the quantity and quality of sleep during layover. Short-haul studies focused on the effects of early starts, late finishes, number of sectors flown and effect of consecutive days working. The CARE model is constructed on the basis of data collected from cabin crew.

Data set used to develop the model…	Cargo operation studies enabled the effects of working consecutive nights to be included in the model. The data from over 500 pilot volunteers were used in the initial construction of the SAFE model and many more have contributed to subsequent updates. The data set forming the basis for SAFE and CARE was formed from a cross section of airlines representing various operator types across the world. SAFE has an associated iPad application (app) for data collection. The data are captured from the app and stored in the model infrastructure for subsequent analysis.
Validation	SAFE has been validated for use specifically by the airline industry from a large data set compiled from more than three decades of studies of aircrew flight duties from commercial air carriers worldwide, on behalf of the UK CAA.
Advantages	• Provides rapid assessment of schedules to identify and measure fatigue risks, and highlight problem areas for further investigation. • The display of analysis results permits problem areas to be easily identified and addressed. • Effective in all types of aviation operation – short-, long- and ultra long-haul operations. • Can be integrated with crew scheduling systems and is suitable for large-scale applications (NB. there is an advisory limit of 150,000 rosters uploaded per single file. The model can accommodate many more, but works most efficiently within this limit). Also has the capacity to interact with industry strength crew optimisers. • Designed for aviation applications and validated specifically for the aviation industry. • Applicable for use by cabin crew via the CARE version. • SAFE is constructed from a large and continually updated database of pilot sleep and fatigue data. Accordingly, the input data requirements are relatively small. • Web-based system that can be called from any computer with Internet access.
Limitations	• Cost may be a consideration for some organisations, although an inexpensive schedule analysis model is available for those who do not wish to licence SAFE. • Extended commute times cannot be entered as a direct input, although these can be input indirectly by altering shift start/end times.
Relevant Publications	Alertness Solutions. (no date). *The System for Aircrew Fatigue Evaluation (SAFE).* Available from: http://www.alertsol.com/downloads/sb_alertsol/AlertnessSolutions_SAFEprogram.pdf Civil Aviation Authority. (2007). *Aircrew fatigue: A review of research undertaken on behalf of the UK Civil Aviation Authority (CAA Paper 2005/04)*. Great Britain: Author. Available from: http://www.caa.co.uk/application.aspx?catid=33&pagetype=65&appid=11&mode=detail&id=1942 (This document provides a detailed overview of the science and processes behind the model and provides numerous relevant references). Mellor, D., & Stone, B. (2012*). Perspectives on the System for Aircrew Fatigue Evaluation (SAFE) predictive alertness model for commercial passenger jet pilots*. Surrey, UK: Fatigue Risk Management Science Limited. Spencer, M.B. (1987). The influence of irregularity of rest and activity on performance: A model based on time since sleep and time of day. *Ergonomics, 30*, 1275-1286. Spencer, M.B. & Robertson, K.A. (2007). The application of an alertness model to ultra-long-range civil air operations. *Somnologie, 11*, 159-166. Spencer, M., & Stone, B. (2011). *The SAFE model* (presentation). Available from: http://www.frmsforum.org/cms_media/files/safe_final1.pdf?static=1 Stone, B., & Mellor, D. (2013). *Analysis of a single monthly Alert Air schedule using the System for Aircrew Fatigue Evaluation (SAFE) model*. Surrey, UK: Fatigue Risk Management Science Limited. Stone, B.M., Spencer, M.B., Rogers, A.S., Nicholson, A.N., Barnes, R., & Green, R. (1993). Influence of polar route schedules on the duty and rest patterns of aircrew. *Ergonomics, 36*(12), 1465-1477.

SAFTE-FAST

Model	**SAFTE-FAST**
Version	SAFTE-FAST 3.6
Institution	Institutes for Behavior Resources, Inc: www.ibrinc.org
Contact	Dr Steven Hursh President, Institutes for Behavior Resources, Inc shursh@ibrinc.org
Description of the Model	Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE) is a biomathematical model of the factors that cause fatigue. It is designed to simulate the underlying physiological system that causes degradations in cognitive performance. The Fatigue Avoidance Scheduling Tool (FAST) implements the SAFTE biomathematical model of performance and fatigue to generate estimates of performance degradation owing to the individual's level of fatigue.
Objective	The purpose of the SAFTE-FAST system is to provide aviation operators with prospective forecasts of expected fatigue risk so that proactive mitigations can be implemented to eliminate excessive fatigue risk. Retrospective and real-time assessments are also supported.
Main Applications	The primary application of the model is to aid operator scheduling by using work schedule information to estimate fatigue and cognitive effectiveness. FAST can be used to examine specific schedules to determine vulnerabilities, to select optimal schedules and to plan napping and recovery sleep strategies.
Outputs	The model provides a number of performance metrics (e.g., percent change in cognitive speed, lapse likelihood, reaction time) and sleep-wake metrics (e.g., sleep reservoir, circadian phase). The outputs of the model are a Manager Table, Summary File and Visual FAST Graphic, all of which provide measurements of both duty time and critical time below an adjustable fatigue risk criterion line.
Cost	The cost of the model is tailored to the size of the corporation. Some features of the system are optional, allowing the customer to scale the cost to their specific needs. Special rates are available for research and government applications. The system can be purchased under an annual license or as a monthly service.
Training and Support	A detailed User Guide is available. Online and face-to-face training are available and the Institutes for Behavior Resources provides telephone support provided by staff members familiar with installation in a variety of settings.
Data set used to develop the model	Several lines of data were used to perfect the model. A large body of data on sleep deprivation and sleep restriction provided by the Walter Reed Army Institute of Research (US DoD), civilian publications on sleep and fatigue, and focused studies by the US Department of Transportation were used. Studies sponsored by the Federal Railroad Administration and the Federal Aviation Administration examined workers in scheduled and unscheduled rail operations, shiftwork operations, and aviation operations.
Validation	Validation studies were conducted by the Walter Reed Army Institute of Research (US DoD) using volunteers in a laboratory setting, the US Federal Railroad Administration sponsored studies looking at accident likelihood and severity in freight rail operations, and US Federal Aviation Administration sponsored studies looking at sleep and performance in flight crewmembers conducting a variety of flight operations (regional, domestic, and international). Some studies have been conducted by private air carriers, which validate the specifics of sleep estimation.
Advantages	• The model claims to distinguish between 'safety critical' work events (called 'crewing') and other events ('non-crewing') and can produce separate effectiveness and sleep reservoir estimates for each. • The model takes into account sleep fragmentation caused by environmental factors such as the quality of in-flight rest facilities. • The model can rank order schedules by mean and minimum effectiveness for all duty time and critical time (defined as 30 mins after takeoff and prior to landing), by minimum sleep reservoir (to indicate whether a schedule will induce excessive sleep debt) and by median or maximum workload.

Advantages…	• The FAST software can graph effectiveness (including percentile deviations), sleep reservoir, circadian phase, and lapse likelihood, along with specific information about the schedule and sun conditions, in Base, GMT, or Local time. • The interface can display a 'dashboard' at any minute in a schedule which summarises the following fatigue factors and displays flags for any factors that is excessive: Sleep in the last 24 hrs, chronic sleep debt, hours awake, circadian time of day, and out of phase (jet lag). • The FAST software has been specifically designed for applications in industrial settings and transport, e.g., for aviation, rail, and shift workers. • A schedule translator is available that can import data from airline scheduling systems, from pairing construction to line building to day of operations. • A version of SAFTE-FAST has been designed specifically for aviation applications. • The outputs of the model include both workload fatigue and cognitive fatigue.
Limitations	• Cost may be a consideration for some organisations, although IBR offers an inexpensive service to evaluate specific schedules and provide a report of findings for organisations that do not wish to licence the model. • Many inputs calculated are based on 'average worker' data. This reduces the inputs required but means the model is less customisable to reflect characteristics of individuals.
Relevant Publications	Gertler, J., Hursh. S., Fanzone, J., & Raslear, T. (2012). *Validation of FAST model sleep estimates with actigraph measured sleep in locomotive engineers* (Report No. DOT/FRA/ORD-12/15). Baltimore, MD: Federal Railroad Administration, U.S. Department of Transportation. Hursh, S.R. (2012). *SAFTE-FAST compared to FAID.* (unpublished document). Hursh, S.R., Raslear, T.G., Kaye, A.S., & Fanzone Jr., J.F. (2007). *Validation and calibration of a fatigue assessment tool for railroad work schedules* (Report No. DOT/FRA/ORD-08/04). Baltimore, MD: Federal Railroad Administration, U.S. Department of Transportation. Institutes for Behavior Resources, Inc. (2012). *Fatigue Avoidance Scheduling Tool (FAST)*. Available from: http://www.ibrinc.org/index.php?id=162 Institutes for Behavior Resources, Inc. (2012). *Fatigue Risk Management Systems (FRMS)*. Available from: http://www.ibrinc.org/index.php?id=71 (This page provides a brief overview of IBR's FRMS services). Institutes for Behavior Resources, Inc. (2014). *SAFTE-FAST for aviation fatigue risk management.* Baltimore, MD: Author. Institutes for Behavior Resources, Inc. *Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE)* website: http://www.ibrinc.org/index.php?id=112

Sleep / Wake Predictor (SWP)

Model	**Sleep / Wake Predictor (SWP)**
Version	2009:1
Institution	Karolinska Institute / Stress Research Institute, Stockholm University, Sweden www.stressforskning.su.se/english/
Contact	Professor Torbjörn Åkerstedt (SWP) Head of Sleep Unit, Stress Research Institute, Stockholm University Head of Stress and Recovery Group, Clinical Neuroscience, Karolinska Institute torbjorn.akerstedt@su.se Michael Ingre (TPMbeta) - Michael.Ingre@su.se
Description of the Model	The Sleep/Wake Predictor model (based on the original Three-Process Model of Alertness) was originally developed by Professor Åkerstedt at the academic Karolinksa Institute and Professor Simon Folkard, University Paris Descartes. It is similar to the basic two-process model, but was developed using several studies with subjective sleepiness ratings. It also accounts for sleep inertia effects, predicts likelihood of sleep onset and sleep termination based on physiological parameters, and has been recently modified to better account for chronic sleep restriction conditions. The software is designed to predict alertness by determining the level of sleepiness associated with changes in circadian rhythms and time awake or asleep. This calculation is used to evaluate the potential for obtaining restful sleep and for a person remaining alert during a specified time period. A new implementation of the Three-Process Model (TPMbeta) has been developed for analysing large databases of individualised work hours and is currently in beta testing. It features a 29 item summary report of sleep, sleepiness risk and alertness opportunity for the schedule or situation under analysis.
Objective	The purpose of the Three-Process Model of alertness underlying the SWP is to assist in the evaluation of general effects of work schedules. Specifically, the aims of the model are to: 1) provide an integrated, quantitative description of the main factors affecting alertness and alertness-related performance; 2) predict alertness from sleep / wake patterns or from work patterns; 3) provide quantitative support for the evaluation of schedules; 4) provide a tool for monitoring alertness and fatigue-related error risk; 5) assist in education on sleep / wake regulation; and 6) provide a tool for generating research hypotheses on sleep/wake regulation and its consequences.
Main Applications	The SWP program is used to assist schedulers and planning staff in evaluating the fatigue and performance effects of particular work schedules. It has been used in a variety of domains including navy, aviation, rail, trucking, nuclear power and military work environments (Transport Canada, 2007).
Outputs	The main output is the predicted alertness curve, in the form of the 1-21 point generic scale or the Karolinska Sleepiness Scale (KSS; 1-9). The software will compute the proportion of total time or work time in which sleepiness levels are above the critical limit. This is one of the key parameters used to summarise the risk level of a particular schedule.
Cost	The algorithms underlying the SWP model have been published and are in the public domain for use without charge. Licences for use of an interactive version of the model with advanced features for the power user are available for purchase by commercial organisations. Use of the recently released TPMbeta model web application is free of charge and is accessible from: https://michaelingre.com/three-process-model/
Training and Support	There is no training or support available for the SWP model.
Data set used to develop the model	Subjective alertness data from a number of experiments of altered sleep/wake patterns were used to develop the SWP model (Gundel et al, 2007) and recent field studies have been undertaken to gather more data for the TPM.

Validation	SWP has been validated in a number of shiftwork studies, a road accident study, and recently a study of aircraft pilots. The Three-Process Model of Alertness underlying the SWP has been successfully validated against EEG parameters and a number of laboratory performance tests.
Advantages	• A free version is available. • The model requires very few inputs in order to make fatigue predictions.
Limitations	• Duty periods are input manually. • Not supplied by a commercial organisation, so support and assistance with interpreting outcomes are not available at this stage. • Detailed user guides are not available. • Not ideal for large-scale roster development.
Relevant Publications	Åkerstedt, T., Ingre, M., Kecklund, G., Folkard, S., & Axelsson, J. (2008). Accounting for partial sleep deprivation and cumulative sleepiness in the three-process model of alertness regulation. *Chronobiology International, 25*(2&3), 309-319. Åkerstedt, T., Folkard, S., & Portin, C. (2004). Predictions from the three-process model of alertness*. Aviation, Space and Environmental Medicine, 75*(3), Section II, A75-83. Gundel, A., Marsalek, K., & ten Thoren, C. (2007). A critical review of existing mathematical models for alertness. *Somnologie, 11*: 148-156. Ingre, M. (2014). TPMbeta web application: https://michaelingre.com/three-process-model/ Ingre, M., Van Leeuwen, W., Klemets, T., Ullvetter, C., Hough, S., Kecklund, G., Karlsson, D., & Åkerstedt, T. (2014). *Validating and extending the Three Process Model of alertness in airline operations.* Manuscript submitted for publication. Transport Canada. (2007). *Fatigue Risk Management System for the Canadian aviation industry: Introduction to fatigue audit tools.* Ministry of Transport, Canada.

8 Model Comparison and Analysis

This section compares the seven biomathematical models being reviewed according to their features and applications. These comparisons are designed to help potential users select a model that best meets their needs. Information is provided in four parts:

- Section 8.1 explains and compares the main applications of each model, so that potential users can match the fatigue risk management needs of their organisation to the functions provided by each model. This is referred to as *Assessment Stage 1*.
- Section 8.2 compares the models on their components, inputs and outputs. This is referred to as *Assessment Stage 2*.
- Section 8.3 details the higher-level evaluation criteria considered relevant to the application of biomathematical fatigue models in aviation contexts.
- Finally, Section 8.4 compares the models against these evaluation criteria, enabling users to determine the model (or models) that best fits the requirements of the organisation.

8.1 Assessment Stage 1: Selecting a model suited to the intended application(s)

The first consideration when selecting a biomathematical fatigue model is to ask whether the model delivers the specific application or applications required by the user organisation. Although all models considered here have the capacity to assist with fatigue management, they have been designed to fulfil different purposes, using different inputs, computations and outputs. Users will need to select a model that is best suited to delivering the intended outcomes.

Table 2 shows the seven biomathematical models and lists for each the applications they provide, as described in Section 5 of this document.

Table 2
Comparison of Model Applications

Model Applications	BAM	CAS	FAID	FRI	SAFE	SAFTE-FAST	SWP
Forward Scheduling	✓	✓	✓	✓[8]	✓	✓	✓
Non-scheduled / Irregular operations	✓	✓	✓	✓	✓	✓[9]	✓
Work / Rest cycles in augmented crew	✓	✓	✓[10]		✓	✓	
Evaluation of light exposure countermeasures	✓	✓					
Evaluation of napping countermeasures	✓	✓			✓	✓[11]	✓
Individual fatigue prediction	✓	✓			✓		✓
Training	✓	✓	✓	✓	✓	✓	✓
Safety Investigation	✓	✓	✓		✓	✓	

Key: ✓ Indicates application is supported by the model

All of the models can be used to assist operators with forward scheduling by helping build schedules that better manage fatigue risk. Compared to other models however, the FRI is somewhat cumbersome when used for large-scale roster production as it was primarily designed for comparing work schedules, and for identifying the fatigue or risk associated with particular shifts. Similarly, the SWP is more suitable for evaluating particular work schedules than for large-scale roster development. The other models have forward scheduling as a primary application and are well suited to the purpose. For instance, BAM, CAS, FAID, SAFE and SAFTE-FAST can be connected to crew planning tools used by larger airlines to support large-scale roster building and modification. BAM and FAID have the capacity to interact with

8 FRI can be used for forward scheduling but was not designed specifically for this purpose and is cumbersome and time-consuming to use for roster building.

9 Available in the ‘RealFAST’ version.

10 Supported in FAID TZ version.

11 Users can schedule naps using FAST to see the effects of napping countermeasures.

industry strength crew optimisers and affect crew schedules during construction. The FAID Roster Tool is a standalone application that provides immediate feedback as a roster is being developed. SAFE can also be configured with the capacity to interact with optimisers and produce fatigue scores in response to new data entered. The other models evaluate rosters after they have been built. All models can be used for short-term scheduling to assess the suitability of duties associated with non-scheduled or irregular operations and several can be used to assist in evaluating work/rest cycles in augmented crews.

Several models have been designed to assist in developing and evaluating fatigue countermeasures. BAM and CAS have the capacity to assist in evaluating countermeasures relating to light exposure, and several models can assist with napping countermeasures. SAFTE-FAST for example incorporates napping as a configurable automatic countermeasure for long wake times prior to duty events, in the form of configurable in-flight naps, and as an explicitly scheduled countermeasure during split duties. Using the graphical tool associated with the model, users can manually insert naps anywhere in a schedule and compare the effects on performance. The SAFE model can also be used in a similar way. FAID does not have the capacity to *evaluate* countermeasures directly, but does provide intra-shift displays of FAID scores to allow targeted risk mitigation strategies (including napping and light exposure) at appropriate times[12]. That is, while FAID cannot calculate the fatigue reduction associated with the implementation of countermeasures such as light exposure, it does enable the times of highest risk within a shift (at which countermeasures may be of most benefit) to be identified. BAM has the capacity to automatically produce fatigue mitigation strategies for a certain point in time, incorporating sleep / wake patterns and timings for light exposure.

BAM, CAS and SWP all allow some individualised data to be input to refine fatigue prediction, while others only incorporate population averages. There are benefits to each approach, with the former permitting outputs to be more customised to individuals, and the latter having fewer and more easily accessible input requirements (i.e. work hours).

Most models can be used to support training of schedulers by helping them to understand the dynamics of the sleep/wake cycle and demonstrating the effects that changes to schedules or nap times, for instance, can have on projected fatigue levels.

The models vary with respect to their applicability for safety investigation (i.e., accident and incident analysis). Some models, such as SAFE and BAM, can be used for this application by allowing the actual sleep of a pilot to be input into the model and enabling the predicted fatigue level at the time of the event to be estimated. Other models, including FRI and FAID, use average population data and while not appropriate for estimating a particular individual’s fatigue level at specific times, have been used for safety investigation purposes by assessing the impact of the individual’s hours of work.

12 Napping can be accounted for within FAID by a break in shift where there is a genuine opportunity and suitable quarters for the person to achieve sleep (generally recommended as at least a one to two hour break).

8.2 Assessment Stage 2: Comparison of Model Features

The second stage in selecting an appropriate biomathematical model is to evaluate specific features of all suitable models, to determine the best fit for the requirements of the organisation.

As discussed in Section 6, biomathematical fatigue models vary in terms of the components that are taken into account, inputs required, and the outputs produced. The components that are incorporated into the various models are shown in Table 3.

Table 3
Comparison of Model Components

Model Components	**BAM**	**CAS**	**FAID**	**FRI**	**SAFE**	**SAFTE-FAST**	**SWP**
Homeostatic Sleep Drive	✓	✓	✓	✓	✓	✓	✓
Circadian Processes	✓	✓	✓	✓	✓	✓	✓
Sleep Inertia	✓	✓		✓	✓	✓	✓
Circadian Phase Adaptation	✓	✓	✓[13]		✓	✓	✓
Work Type	✓	✓		✓	✓	✓	
Time on Task	✓	✓	✓	✓	✓	✓	✓

Key: ✓ Indicates the component is incorporated into the model

Table 3 shows a high degree of commonality in the underlying components of the models. All models account for homeostatic sleep drive and circadian processes. All except FAID take into account the effects of sleep inertia[14], and all but FRI account for circadian phase adaptation.

Many of the models take work type into account, although the way in which they do this varies. SAFE calculations assume different levels of workload for *office duties*, *training*, *simulator activities*, *flying duties* and *cabin crew duties*, and the FRI similarly takes the type of activity being undertaken during the shift into account within fatigue risk calculations. CAS does not focus on specific job types but does incorporate several workload categories which distinguish between *flight crew* and *cabin crew*, between *flight crew performing training*, *flying* or *on-duty but not flying*, and between *take-off* and *landing* phases versus other phases of flight, for example. BAM and SAFTE-FAST similarly distinguish between different duty types, so that pilots flying multiple short-range flight sectors over a short time period will have a higher calculated workload than those flying a longer single sector, for example.

While FAID does not incorporate work type into model calculations, it does take work-related fatigue exposure into account during interpretation of the results. For instance, a lower FAID score benchmark figure (Fatigue Tolerance Level) may be set for tasks or roles designated as higher-risk, and a higher level for tasks or roles designated as lower-risk (up to three task risk benchmark figures may be set within the same data set). Similarly, SAFTE-FAST users can

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[13] FAID TZ version only.

[14] Given that FAID does not incorporate sleep inertia as a model component, the suppliers advise that at least 10 minutes of wake-up time be allowed before any safety-critical tasks are undertaken to allow for dissipation of sleep inertia effects.

set different effectiveness criteria for specific work groups to account for differences in risk associated with their activities. SAFTE-FAST calculates a separate workload factor based on the density of flight segments and reports it as a separate component of fatigue. All models take time on task into account.

The required and optional inputs for the various models considered in this review are shown in Table 4.

Table 4
Comparison of Model Inputs

Model Inputs	**BAM**	**CAS**[15]	**FAID**[16]	**FRI**	**SAFE**	**SAFTE-FAST**	**SWP**
Actual sleep timing	Op	Op	Op[17]		Op	Op	Op
Work schedule	✓	✓	✓	✓	✓	✓	✓
Time zone changes	✓	Op	✓			✓	✓
Crew composition	✓	✓	Op		✓	✓	
In-flight rest facilities (bunk or seats)	Op	Op	Op		✓	Op	
Take off and landing waypoints	✓	✓	✓		✓	✓	
Multiple sectors	✓	✓	Op		✓	✓	
Workload		Op	Op	✓			
Habitual sleep duration	Op	Op			Op		Op
Chronotype	Op	Op					Op
Commuting	✓	Op	Op	✓	Op	Op	

Key: ✓ Required input
Op Optional input

Table 4 shows that many models can incorporate actual sleep / wake timing as an optional input, overriding model predictions of sleep and wake. This feature is often used in models such as SAFE when being used to investigate fatigue reports or incidents and accidents that could have a fatigue-related element. All models have work schedule as a required input.

The models vary considerably in terms of inputs relating to time zone changes, crew composition, sleep location, take off and landing waypoints and number of sectors. Many models require time zone changes as an input. Others, including SAFE and CAS, do not require time zone changes as a specific input but calculate these automatically from airport codes. BAM, CAS, SAFE and SAFTE-FAST require inputs relating to crew composition (e.g., single pilot / multi-crew / augmented or non-augmented crew) to produce estimates. This is an optional input in FAID TZ. SAFE permits cabin crew as an additional crew composition option.

[15] Some of the optional inputs can only be incorporated via the Graphical User Interface that supplements the CAS.

[16] Some of these inputs are available only in the FAID TZ version.

[17] FAID TZ only permits the input of planned and actual in-flight augmented rest/sleep periods.

Several models also take into account location of sleep (bunk or seats) as an indicator of sleep quality. Different models use different categories for these inputs. For instance, SAFE allows use of *bunk*, *business passenger seat*, *flight deck seat*, *economy seat* and *jump seat* as input options, SAFTE-FAST considers four levels of sleep quality, CAS can consider *home*, *hotel* and *inflight* (economy/business/bunk) sleeping locations and FAID TZ considers different quality of in-flight rest by a recovery factor based on research on in-flight sleeping conditions.

Many models require inputs regarding takeoff and landing waypoints. In some models, such as CAS, this input is used to derive other information such as time zone changes. BAM, CAS, SAFE and SAFTE-FAST all require direct inputs on the number of sectors. SAFE and SAFTE-FAST use this input to calculate workload. The FRI requires both workload and the attention demand of the shift as an input so that these can be taken into account in determining the fatigue risk. FAID allows for a designation of Task Risk level as an input which, while not changing the calculation, can be used as a proxy for category of workload, with measures highlighted accordingly in the outputs. CAS can incorporate workload as an optional input and can take this into account in calculation of fatigue risk scores.

In regard to the individualisation of models, BAM, CAS and SWP can be configured to incorporate individual sleep need (habitual sleep duration) and individual chronotype. In CAS, individualisation also incorporates *short or long sleeper*, *napper or consolidated sleeper* and *flexible or rigid sleeper* categories. BAM and CAS can also incorporate commute times to further refine estimates. SAFE can incorporate habitual sleep duration (all sleep periods are configurable by the user), but not the other individual inputs. SAFE, SAFTE-FAST and FAID generally use population averages for inputs such as chronotype and commute times rather than individualised data, so that fewer inputs are required. SAFTE-FAST can incorporate specific commute times for individual fatigue reports and have the outputs recalculated accordingly, but works on set commute times (based on standard commute times or commute times based on the location) in batch processing. Other models can accommodate changes in commute times indirectly. In FAID TZ and SAFE, for instance, extended commute times can be modelled indirectly by editing inputs such as the start and finish times. Similarly, FAID TZ can only incorporate multiple sectors indirectly, by entering the duty time as a series of component activities with different start and end periods so that multiple sectors are identified as separate work activities. The FRI and SWP require very few inputs in order to produce fatigue predictions.

The third criterion for comparison is the output produced by the models, shown in Table 5.

Table 5
Comparison of Model Outputs

Model Outputs	**BAM**	**CAS**	**FAID**	**FRI**	**SAFE**	**SAFTE-FAST**	**SWP**
Subjective alertness	✓	✓	✓	✓	✓		✓
Estimated sleep / wake times	✓	✓	✓		✓	✓	✓
Performance		✓	✓			✓	✓
Fatigue-related task errors		✓				✓	✓
Fatigue-related risk of operational accidents		✓	✓	✓		✓	✓
Confidence intervals	✓					✓	✓

Key: ✓ Indicates factor is an output of the model

As shown in Table 5, all models except SAFTE-FAST produce a fatigue or alertness prediction value over a given work period, referred to as a ‘subjective alertness metric’. SAFTE-FAST does, however, report subjective workload based on density of flight segments. All models except the FRI produce estimated sleep and wake times as outputs. CAS, FAID, SAFTE-FAST and SWP aim to provide performance-based metrics. For instance SAFTE-FAST is designed to predict effectiveness (cognitive throughput), reaction time, lapse likelihood, and average cognitive performance. SAFE does not currently incorporate a performance metric but previous version did indicate predicted reaction times and predicted vigilance performance, and it is intended that these will be reinstated in a future version.

Several models predict the probability of fatigue-related risk of task error or of operational accidents. In regard to the former, SAFTE-FAST predicts changes in reaction time and increases in fatigue-related lapses of attention. The current version of SAFE does not predict the fatigue-related risk of task error, but this will be incorporated in the upcoming version of the model. In regard to the fatigue-related risk of operational accidents, the CAS, for example, incorporates a Fatigue Risk Index, which claims to be a sensitive measure of the risk of incidents, accidents and injury in multiple transportation modes. Based on validation studies, these relate directly to changes in railroad accident likelihood and severity. FAID provides increasing colour bands of risk, representing the increasing risk of fatigue-related operational accidents.

BAM and SWP produce outputs incorporating confidence intervals. SAFTE-FAST does not produce standard confidence intervals around the mean, but instead reports and graphs the percentile variations from the mean, based on estimates of the standard deviation of performance for a population of subjects. For example, the model can display the lowest 20th percentile subject along with the average subject performance.

8.3 Evaluation Criteria

The previous sections have identified specific features of the various models in terms of their components, inputs and outputs. There are also higher-level evaluation criteria that may assist organisations to select the model most appropriate for their requirements.

A set of these broader evaluation criteria, which are considered relevant to the application of biomathematical fatigue models in aviation contexts, are detailed below.

Cost

Cost is an essential consideration for any organisation in selecting tools or business processes to acquire. Unfortunately, a direct cost comparison of models reviewed in this document is not possible, as purchase costs will in most cases vary considerably depending on the size and requirements of the purchasing organisation. Where cost information is available, this has been incorporated into the descriptions of the models in Section 7.

Capacity to incorporate individual-specific data

Most biomathematical models are based on ‘average person’ predictions for target populations, so the primary application of models is to assess or compare shifts rather than the characteristics or likely response of an individual. Some models have the capacity to refine fatigue estimates through the inclusion of data from individuals. This criterion may be important if an organisation plans to support an individual fatigue management program or to use the model for incident or accident investigation.

Potential for integration with Crew Scheduling Systems

This refers to the capacity of the model to be integrated or linked to the existing Crew Scheduling System. This is an important criterion if an organisation plans to conduct a systematic evaluation of pairings or bid lines (as discussed in Section 5.1).

Suitability for large-scale application

This reflects the capacity of the model to handle large data samples (e.g., to import multiple schedules from spreadsheets). This criterion will be essential for large operators as some models only allow a manual input of rosters.

Capacity to incorporate time zone changes

The capacity of a model to take into account effects associated with time zone changes greater than three hours is an additional criterion that will be essential for some organisations to consider. This criterion will be important for an airline that operates transmeridian flights, as the predictions will need to account for the rate of body clock adjustment.

Capacity to consider multiple flights within a single work period

This refers to the capacity of a model to take into account effects associated with multiple sector duty patterns. This is essential for airlines operating domestic or regional operations flying multiple sectors, and can also be critical for charter, tourism, agricultural and emergency services operations. For instance, it has been established that the number of sectors has a significant linear effect on fatigue in short-haul operations (Robertson & Spencer, 2003; Spencer & Robertson, 2002), with one study reporting that each additional sector leads to an increase in fatigue equivalent to 0.38 on the 7-point Samn Perelli (SP) fatigue rating scale (Powell et al, 2007).

Capacity to incorporate actual sleep data

Within the framework of an FRMS, airlines may be able to collect sleep data on specific rosters. Some models have the capacity to refine fatigue estimates using actual sleep data. This is an important criterion as fatigue predictions from actual sleep data are considered to be more accurate and more valid than fatigue predictions based on scheduled work hours.

Capacity to consider workload

Another evaluation criterion is the capacity of a model to change fatigue prediction according to levels of workload. This criterion is important to consider for organisations that are required to make fatigue predictions for different categories of workers (pilots, cabin crew, ground staff, etc.) or for accounting for the variations in workload experienced over the duration of a work period. The capacity to incorporate the level of workload and its fluctuation during the shift can enable more accurate fatigue predictions to be produced.

Availability of guidance on model capabilities and limitations

The availability of guidance on the capabilities, limitations and deployment of models is another important evaluation criterion, so that intending users can assess the suitability of a model for use within their organisation. Ideally, this information would address issues including the dimensions of fatigue that are considered by the model, the mechanisms by which they are considered, data sets that have been used to validate the model, and the cautions and limitations that should apply to interpretation of model outputs. Model suppliers have a duty of care to ensure that available information is comprehensive, accurate and does not overstate or misrepresent model capabilities (Civil Aviation Safety Authority, 2010). As with the criteria relating to cost, a direct comparison of models reviewed in this document was difficult for this criterion given the diversity of information available, and the criterion is therefore not incorporated into the evaluation summary in the next section. It is nonetheless recommended that model users take into account the availability and quality of this information when selecting an appropriate model.

Availability of training, support and user guidance documentation on model implementation and use

A key issue to assist with successful deployment and application of any biomathematical model is ensuring that decision makers and schedulers from operators are effectively trained in the features, limitations and use of the model. Most of the models selected for this review have some form of training available and intending users should ensure that a training program for relevant staff is included within the specification for the model negotiated with suppliers. Like the previous criterion, the availability of training, support and user guidance documentation is not summarised in the evaluation table as the models vary considerably in the quantity and scope of the support provided. Where this information is available, however, it has been incorporated into the descriptions of the models in Section 7.

Validated for aviation use

The question of whether a model has been validated in the aviation context is the final evaluation criterion considered in this review. Depending on the requirements of the particular user, it may be important to consider whether the data used to develop and validate a model is relevant given the target operational environment and subject population. It is difficult provide a direct comparison of models in relation to validation details, as there is considerable variation on the scope, size, purpose and data set of validation studies, as well as their quality (established, for example, by whether they have been published and peer reviewed). A summary of the model dataset and validation information has been incorporated into the descriptions of the models included in Section 7 and a highly simplified indication of whether or not the model has been validated in the aviation context is provided as part of the summary of Evaluation Criteria in Section 8.4. Operators are strongly advised, however, to investigate for themselves the quality and scope of any validation data when selecting a model.

8.4 Comparison of Models against Evaluation Criteria

This section evaluates the various biomathematical fatigue models against the set of higher-order evaluation criteria described in Section 8.3. Table 6 shows the models and whether the evaluation criteria are met.

Table 6
Comparison of Models on Evaluation Criteria

Evaluation Criteria	**BAM**	**CAS**	**FAID**[18]	**SAFE**	**SAFTE-FAST**	**FRI**	**SWP**
Capacity to incorporate individual-specific data	✓	✓		✓			✓
Potential for integration with Crew Scheduling Systems	✓	✓	✓	✓	✓		✓
Suitable for large scale application	✓	✓	✓	✓	✓	✓[19]	
Capacity to incorporate time zone changes	✓	✓	✓	✓	✓		✓
Capacity to consider multiple flights within a single work period	✓	✓	✓	✓	✓		
Capacity to incorporate actual sleep data	✓	✓	✓[20]	✓	✓		
Capacity to consider workload	✓	✓	✓	✓	✓	✓	
Validated for use in aviation	✓	✓	✓	✓	✓	✓	✓

Key: ✓ Meets evaluation criterion

The criterion of cost could not be summarised or compared easily because the fees associated with the various models typically depend on the size and requirements of the organisation. One model, the FRI, is available free of charge and the SWP, BAM and FAID models also have free versions available, but for price details, organisations will need to contact the relevant supplier to discuss fees.

The capacity to refine fatigue estimates by incorporating individual-specific data is supported by several models. BAM and CAS can take a range of individual data, such as commute times, individual chronotype and individual sleep need into account. SAFE generally uses population average data, but can incorporate individual data to refine estimates, and does so frequently when the model is being used to assist with incident and accident investigation.

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[18] Most of the evaluation criteria ratings apply to FAID TZ.

[19] It is possible to use FRI for large-scale application but the model is cumbersome for use on large numbers of different schedules. FRI is better suited to small-scale applications.

[20] FAID TZ only permits the input of planned and actual in-flight augmented rest/sleep periods.

SAFTE-FAST and FRI take no account of individual factors as all inputs are based on population estimates. Similarly FAID scores provide indications of relative fatigue exposure and do not necessarily indicate the level of individual fatigue.

All models except FRI can be integrated with crew scheduling systems and all except FRI and SWP are suitable for large-scale applications, although the capacities and speeds of the models do vary[21]. As noted above, BAM and FAID can interact with industry strength crew optimisers and affect crew schedules while they are built, while most other models evaluate rosters after construction.

All models except FRI can incorporate time zone changes, although for FAID this is only available in the FAID TZ and FAID Roster Tool TZ versions. FRI and FAID Standard may be more applicable for organisations that are not operating over multiple time zones.

The capacity to consider multiple flights within a single work period is relevant because the number of sectors operated is related to the workload of a duty period. BAM, CAS, SAFE and SAFTE-FAST take the number of sectors into account in their calculations. FAID TZ does not consider number of sectors specifically in fatigue estimates, but does enable each leg/segment or component activity to be listed separately. In CAS and SAFTE-FAST, the time between each leg/segment can be assigned as either duty (no sleep opportunity) or sleep opportunity. FAID TZ reports each activity separately in the outputs so that a separate assessment of hours of work fatigue exposure is calculated for each component activity.

Several models permit actual sleep data as an input to refine estimates, although in FAID TZ, only actual in-flight augmented sleep/rest periods can be input. Most models take consideration of workload.

All models have all been validated for use in aviation to some extent, although, as discussed in Section 8.3, there is considerable variation in the form that these validation studies have taken and operators are advised to investigate for themselves the quality, scope and relevance of a model's validation studies before selecting it for use.

[21] See the model descriptions in Section 7 for details.

9 Conclusion

This document reviews a selected group of biomathematical fatigue models with respect to their suitability for use as a component of an effective FRMS within the civil aviation industry. The included models were selected on the basis of factors including their availability and suitability for use within the aviation environment, their scientific basis and rigour, and their capacity to contribute to the identification and management of fatigue risk within the operational environment.

Information on the models was compiled from various sources, including a blend of available peer-reviewed publications, promotional material, and self-reported responses from current vendors or suppliers of the respective models. The scope of this review, however, did not extend to independent field trials of any of the models. Prospective users are thus advised to use this document for initial guidance, but to then carry out their own evaluations as to whether a specific model is suitable for deployment for the operating environment and activities most relevant to them.

It should be noted that while this document reflects the current status of biomathematical fatigue modelling, this is an area of continuing research and rapid development and it is expected that there will be significant enhancements to fatigue modelling science in the near future, including the capacity to predict specific risks associated with fatigue.

Biomathematical fatigue models have the unique benefit of enabling scientific knowledge on fatigue, gained from empirical observations and research studies, to be incorporated into work scheduling decisions. Prospective users are also reminded, however, to carefully consider the generic cautions and limitations of biomathematical models discussed within this document before putting any such models to use. While these models can be very useful tools to assist with the identification and management of fatigue risk, they should only ever be considered as one element of a comprehensive FRMS.

Glossary [22]

Actigraphy	A process to monitor and analyse sleep patterns through use of an actiwatch (a wristwatch-like device containing an accelerometer to detect movement) or similar device. Actiwatches provide graphs of movement (actigraphs) as output, and are able to record data continuously for several weeks at a time, so they are valuable tools for monitoring sleep patterns, for example, before, during, and after a trip. For actigraphy to be a reliable measure of sleep, the computer algorithm that estimates sleep from activity counts must have been validated against polysomnography, which is the gold standard technology for measuring sleep duration and quality. This technique is well suited for FRMS applications as it provides a good estimate of actual sleep duration and quality. It does not, however, allow identification of sleep stages (see non-REM sleep), as does polysomnography. It is often used in conjunction with a sleep diary.
Augmented Flight Crew	A flight crew that comprises more than the minimum number required to operate the aeroplane so that each crew member can leave his assigned post to obtain in-flight rest and be replaced by another appropriately qualified crew member.
Augmented Long-Range Operations	Flights where the scheduled flight duty period is extended through the use of augmented crews (additional crew members), allowing all crew the opportunity for in-flight rest.
Bid line	A sequence of flight crew roster pairings that has been pre-built into a 'legal' pattern using a computer program, usually on a monthly or two-monthly basis, then made available for bidding (requesting of that specific bid line / duty schedule) by flight crew.
Biomathematical model	A tool designed to predict crewmember fatigue levels, based on scientific understanding of the factors contributing to fatigue. Biomathematical models are an optional tool (not a requirement) for predictive fatigue hazard identification, as within an FRMS. All biomathematical models have limitations that need to be understood for their appropriate use in an FRMS.
Chronic fatigue	In fatigue risk management, chronic fatigue refers to the state resulting from the sleepiness and performance impairment that accumulate when sleep is restricted on a number of consecutive days (also see cumulative sleep debt).
Chronotype	Circadian chronotype is an attribute reflecting the time of day that a person's physical functions (hormone level, body temperature, cognitive faculties, eating and sleeping patterns) are active, change or reach a certain level. The most commonly recognised aspect of this phenomenon relates to an individual's predisposition to be either a 'morning type' (one who prefers to wake up early and is more alert in the early hours of the day) or an 'evening type' (one who is more alert in the late evening hours and prefers going to bed late). This predisposition can change as people age.

[22] This Glossary is in part adapted from information provided within ICAO's *FRMS Manual for Regulators* (International Civil Aviation Organization, 2012a) and the *FRMS Implementation Guide for Operators* produced by the global aviation industry FRMS Task Force (IATA, ICAO & IFALPA, 2011).

Circadian Body Clock	A neural pacemaker in the brain that monitors the day/night cycle (via a special light input pathway from the eyes) and determines our preference for sleeping at night. Shift work is problematic because it requires a change in the sleep/wake pattern that is resisted by the circadian body clock, which remains 'locked on' to the day/night cycle. 'Jet lag' is problematic because it involves a sudden shift in the day/night cycle to which the circadian body clock must adapt.
Controlled Rest on the Flight Deck	An effective mitigation strategy to be used as needed in response to fatigue experienced or anticipated during long-haul flight operations. It should not be used as a scheduling tool component (i.e., as a planned strategy to enable extended duty periods).[23]
Countermeasures	Personal mitigation strategies that individuals can use to reduce their own fatigue risk. Sometimes divided into strategic countermeasures (for use at home and away, for example good sleep habits, napping before night duty), and operational countermeasures for use in flight, for example controlled rest on the flight deck (see above).
Crewmember	A person assigned by an operator for duty on an aircraft during a flight duty period.
Crew pairing	A set of scheduled flights on which a crewmember is rostered for one or more days.
Crew Resource Management training (CRM)	A team training and operational philosophy originating within the aviation industry. Defined as the use of all available resources – information, equipment, and people – to achieve safe and efficient flight operations (Lauber, 1984, p. 20).
Cumulative sleep debt	Sleep loss accumulated when sleep is insufficient for multiple nights (or 24-hr days) in a row. As cumulative sleep debt builds up, performance impairment and objective sleepiness increase progressively, and people tend to become less reliable at assessing their own level of impairment.
Duty	Any task that crew members are required by the operator to perform, including, for example, flight duty, administrative work, training, crew positioning and standby when it is likely to induce fatigue.
Duty period	A period which starts when a flight or cabin crew member is required by an operator to report for or to commence a duty and ends when that person is free from all duties.
Fatigue	A physiological state of reduced mental or physical performance capability resulting from sleep loss or extended wakefulness, circadian phase, or workload (mental and/or physical activity) that can impair a crew member's alertness and ability to safely operate an aircraft or perform safety related duties.
Fatigue risk management	The management of fatigue in a manner appropriate to the level of risk exposure and the nature of the operation, in order to minimise the adverse effects of fatigue on the safety of operations.

[23] Recommended procedures for controlled rest on the flight deck are included at Appendix C to the *FRMS Implementation Guide for Operators* (see IATA, ICAO & IFALPA, 2011).

Fatigue Risk Management System (FRMS)	A data-driven means of continuously monitoring and managing fatigue-related safety risks, based upon scientific principles and knowledge as well as operational experience that aims to ensure relevant personnel are performing at adequate levels of alertness.
FRMS Policy	A required component of an aviation FRMS (see International Civil Aviation Organization, 2010). The FRMS Policy must: identify the elements of the FRMS and its scope; reflect the shared responsibility of all stakeholders in the FRMS; state the safety objectives of the FRMS; be signed by the accountable executive of the organisation; be communicated throughout the organisation; declare management commitment to effective safety reporting, to providing adequate resourcing for the FRMS, and to continuous improvement of the FRMS; identify clear lines of accountability for the functioning of the FRMS; and require periodic reviews of the FRMS.
FRMS safety assurance	FRMS safety assurance processes monitor the entire FRMS to check that it is functioning as intended and meeting the safety objectives in the FRMS policy and regulatory requirements. FRMS safety assurance processes also identify operational and organizational changes that could potentially affect the FRMS, and identify areas where the safety performance of the FRMS could be improved (continuous improvement).
FRMS Training	Competency-based training programs designed to ensure that all stakeholders are competent to undertake their responsibilities in the FRMS.
Fatigue Safety Action Group (FSAG)	A group comprised of representatives of all stakeholder groups (management, scheduling, crew representatives) together with specialist scientific, data analysis, and medical expertise as required), that is responsible for coordinating all fatigue management activities in the organisation.
Flight Data Analysis (FDA)	A process of collating and analysing recorded flight data parameters in order to improve the safety of flight operations. See also Flight Operational Quality Assurance (FOQA).
Flight duty period	A period which commences when a crew member is required to report for duty that includes a flight or a series of flights and which finishes when the aeroplane finally comes to rest and the engines are shut down at the end of the last flight on which he/she is a crew member.
Flight Operational Quality Assurance (FOQA)	FOQA (also known as FDA) is a voluntary safety program designed to improve aviation safety through the proactive use of di-identified and aggregated data from on-board flight recorders.
Homeostatic sleep	See Sleep homeostatic process.
Human factors	Human factors is a multidisciplinary field concerned with optimising the performance of individuals and teams in the workplace. The broad domain of human factors is an applied science that draws on methods and principles from psychology, other behavioural and social sciences, engineering, ergonomics and physiology. The aim of human factors is to reduce and mitigate error and improve safety and efficiency through an understanding of human capabilities, limitations and the way people interact with their work environments.

Jet lag	Desychronisation between the circadian body clock and the day/night cycle caused by transmeridian flight (crossing at least 3 time zones; experienced as a sudden shift in the day/night cycle). This results in internal desychronisation between rhythms in different body functions. Common symptoms include wanting to eat and sleep at times that are out of step with the current local routine, problems with digestion, degraded performance on mental and physical tasks, and mood changes. Resolves when sufficient time is spent in the new time zone for the circadian body clock to become fully adapted to local time.
Microsleep	A short period of time (a few seconds) when the brain disengages from the environment (it stops processing visual information and sounds) and slips uncontrollably into light non-REM sleep. Micro sleeps are a sign of extreme physiological sleepiness.
Mitigations	System-level interventions designed to reduce a specific identified fatigue risk. Examples include: increasing the number of crew members at a base, use of reserve crew, educating crewmembers on how to obtain optimal in-flight sleep, Captain's discretion to re-organise in-flight rest arrangements on the day of flight (in response to crewmembers' fatigue levels and operational conditions, etc).
Nap	A brief period of sleep, usually defined as less than half of a full night time sleep period, but often as short as 20 to 25 minutes, colloquially known as a 'NASA nap' or 'power nap'. Naps as short as 5 minutes have been shown to provide (temporary) relief from the cumulative effects of sleep loss. See also Controlled Rest on the Flight Deck.
Non-Rapid Eye Movement Sleep (Non-REM Sleep)	A type of sleep associated with gradual slowing of electrical activity in the brain (seen as brain waves measured by electrodes stuck to the scalp, known as EEG). As the brain waves slow down in non-REM sleep, they also increase in amplitude, with the activity of large groups of brain cells (neurons) becoming synchronised. Non-REM sleep is usually divided into 4 stages, based on the characteristics of the brainwaves. Stages 1 and 2 represent lighter sleep. Stages 3 and 4 represent deeper sleep and are also known as slow-wave sleep or deep sleep. Slow wave sleep is directly involved in the recovery of sleep debt and appears mostly in the first part of a sleep period.
Non-REM / REM Cycle	Regular alternation of non-REM sleep and REM sleep across a sleep period, in a cycle lasting, on average, approximately 90 minutes.
Polysomnography	Refers to the process of studying a person while asleep by taking comprehensive recordings of numerous physiological parameters (brain waves, eye movements, muscular activity, etc.).
Rapid Eye Movement Sleep (REM Sleep)	A type of sleep during which electrical activity of the brain resembles that during waking. However, from time to time the eyes move around under the closed eyelids – the 'rapid eye movements' – and this is often accompanied by muscle twitches and irregular heart rate and breathing. People woken from REM sleep can typically recall vivid dreaming. At the same time, the body cannot move in response to signals from the brain, so dreams cannot be 'acted out'. The state of paralysis during REM sleep is sometimes known as 'REM block'. REM sleep is involved in the maintenance of cognitive functions, especially related to memory. REM sleep mostly occurs toward the end of the sleep period.

Recovery sleep	Sleep required for recovery from the effects of both acute sleep loss (in one 24-hour period), or cumulative sleep debt (over multiple consecutive 24-hour periods). Recovery sleep may be slightly longer than usual, but lost sleep is not recovered hour-for-hour. Two nights of unrestricted sleep (when a crewmember is fully adapted to the local time zone) are typically required for recovery of normal sleep structure (non-REM/REM cycles). Recent laboratory research suggests that recovery of optimal waking function may take more than two nights of recovery sleep.
Rest period	A continuous and defined period of time subsequent to and/or prior to duty, during which flight or cabin crew members are free of all duties.
Risk Management	The systematic processes used to identify, analyse, evaluate, treat and monitor hazards or other conditions and events that could cause harm or loss.
Roster / Rostering	Assignment of crewmembers to a specific work pattern or schedule.
Safety culture	The set of beliefs, norms, attitudes, and practices within an organisation concerned with minimising exposure of the workforce and the general public to dangerous or hazardous conditions. In a positive safety culture, a shared concern for, commitment to and accountability for safety is promoted.
Safety management	The systematic management of the operational risks associated with flight, engineering and ground activities in order to achieve as high a level of safety performance as is reasonably practicable.
Safety Management System (SMS)	A systematic approach to managing safety, including the necessary organisational structures, accountabilities, policies and procedures.
Safety performance	The level of safety achieved in a risk-controlled environment measured against a safety level deemed as low as reasonably practicable.
Schedule	Sequence of flights designed to meet operational requirements and effectively manage resources including crewmembers.
Shift work	Any work pattern that requires a crewmember to be awake at a time in the circadian body clock cycle that they would normally be asleep. Problematic because the circadian body clock is sensitive to light and tends to remain 'locked on' to the day/night cycle rather than adapting to the work pattern. Shift work is usually associated with sleep restriction, together with a requirement to work during times in the circadian body clock cycle when performance and alertness are sub-optimal (for example, through the Window of Circadian Low).
Sinusoidal function	The sine wave or sinusoid is a mathematical curve that describes a smooth repetitive oscillation. Circadian rhythms follow a sinusoidal function.
Sleep	A reversible state in which conscious control of the brain is absent and processing of sensory information from the environment is minimal. The brain goes "off-line" to sort and store the day's experiences and replenish essential systems depleted by waking activities. A complex series of processes characterised by alternation between two different brain states: non-REM sleep and REM sleep.

Sleep debt	See Cumulative Sleep Debt.
Sleep diary (or sleep log)	A self reported record of individual sleep timing and duration over several days or weeks. A sleep diary is often used in conjunction with actigraphy.
Sleep Homeostatic Process	The body's need for slow-wave sleep (non-REM stages 3 and 4), that builds up across time spent awake and discharges exponentially across time spent asleep.
Sleep inertia	Transient disorientation, grogginess and performance impairment that can occur as the brain progresses through the process of waking up. Sleep inertia can occur on waking from any stage of sleep but may be longer and more intense on waking from slow-wave sleep (non-REM stages 3 and 4).
Sleep need	The amount of sleep that is required on a regular basis to maintain optimal levels of waking alertness and performance. Very difficult to measure in practice because of individual differences. In addition, because many people live with chronic sleep restriction, when they have the opportunity for unrestricted sleep, their sleep may be longer than their theoretical 'sleep need' due to recovery sleep.
Sleep quality	Capacity of sleep to restore waking function. Good quality sleep has minimal disruption to the non-REM/REM cycle. Fragmentation of the non-REM/REM cycle by waking up, or by brief arousals that move the brain to a lighter stage of sleep without actually waking up, decreases the restorative value of sleep.
Sleep restriction	Obtaining less sleep than needed ('trimming' sleep) across at least two consecutive nights. The effects of sleep restriction accumulate, with performance impairment and objective sleepiness increasing progressively. The need for sleep will eventually build to the point where people fall asleep uncontrollably (see micro-sleep).
Slow-wave sleep	The two deepest stages of non-REM sleep (stages 3 and 4), characterised by high amplitude slow brainwaves (EEG dominated by 0.5-4 Hz).
Standby / Standby duty	A defined period of time, at the airport, at the hotel, or at home, during which a flight or cabin crew member is required by the operator to be available to receive an assignment for a specific duty without an intervening rest period.
Transient fatigue	Impairment accumulated across a single duty period, from which complete recovery is possible during the next rest period.
Trip	A scheduling expression describing the time from when a crewmember initially reports for duty until he/she returns home from the sequence of flights and is released from duty. A trip may include multiple flights and many days of travel.
Ultra Long Range Operations (ULR)	Augmented long-range operations involving any sector between a specific city pair in which the planned flight time exceeds 16 hours, taking into account mean wind conditions and seasonal changes (as defined by the Ultra long range Crew Alertness Steering Committee, Flight Safety Foundation (2005). Flight Safety Digest 26.)

Unforeseen operational circumstance	An unplanned event, such as un-forecast weather, equipment malfunction, or an air traffic control delay, that is beyond the control of the operator. In order to be considered unforeseen, the circumstance would occur or become known to the operator after the flight has begun.
Unrestricted sleep	Sleep that is not restricted by duty demands. Sleep can begin when a crewmember feels sleepy, and does not have to be delayed or curtailed because of duty demands. In addition, the crewmember can wake up spontaneously and does not have to set the alarm to be up in time for duty.
Window of Circadian Low (WOCL)	Time in the circadian body clock cycle when subjective fatigue and sleepiness are greatest and people are least able to do mental or physical work. The WOCL occurs around the time of the daily low point in core body temperature - usually around 03:00-05:00 hours when a person is fully adapted to the local time zone. However, there is individual variability in the exact timing of the WOCL, which is earlier in morning-types (larks) and later in evening-types (owls), and may move a few hours later after consecutive night shifts.

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