CASA Biomathematical Fatigue Models Guidance Document Summary

In 2010 the Australian Civil Aviation Safety Authority (CASA) published a paper titled '*Biomathematical Fatigue Modelling in Civil Aviation Fatigue Risk Management: Application Guidance*'. In March 2014 an updated version of this document titled *'Biomathematical Fatigue Models Guidance Document'* was released. The intent of the documents is to provide the aviation industry with updated guidance on the application of biomathematical fatigue models (BFMs) for use as optional components of Fatigue Risk Management Systems (FRMS). The document was specifically developed to help operators decide whether to use a biomathematical fatigue model in their FRMS; and if so which model.

This paper seeks to summarise the 73 page *Biomathematical Fatigue Models Guidance Document* focusing on the applications, limitations and cautions on the use of BFMs (Sections 5, 2.1 and 2.2 respectively).

The CASA *Biomathematical Fatigue Models Guidance Document* also contains sections on the science behind fatigue modelling (Section 3), model characteristics and structure (Section 6), a summary of seven biomathematical fatigue models (Section 7) and model comparison, analysis and conclusion (Sections 8 & 9). This information has not been summarised here. The CASA document contains references which have not been reproduced in this document. As CASA are an Australian regulator, Australian terminology and spelling has been used in the document and this summary. Please refer to the CASA *Biomathematical Fatigue Models Guidance Document* for further information and references.

Acronyms

BFM	Biomathematical Fatigue Model
CASA	Australian Civil Aviation Safety Authority
FRMS	Fatigue Risk Management System
FTL	Flight and Duty Time Limitation
ICAO	International Civil Aviation Authority

1. Biomathematical Fatigue Models (BFMs): Definition

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. [1]

2. Applications of Biomathematical Fatigue Models

(Refer CASA, 2014, Biomathematical Fatigue Models Guidance Document, Section 5: Model Applications pp. 23-27)

Potential applications of BFMs include:

- Forward Scheduling
- Non-scheduled / Irregular Operations
- Work / Rest Cycles in Augmented Crew
- Light Exposure and Napping Countermeasures
- Individual Fatigue Prediction
- Training
- Safety Investigation

2.1. Forward Scheduling

A primary application of BFMs 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 safety risk.

An important application of BFMs is to assist with developing optimal crew schedules. 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, BFMs can be used to assist in the development of work schedules that reduce fatigue-related safety risk.

When applying BFMs for scheduling purposes, it is important to recognise the limitations of their use, as discussed later in this document (refer Sections 3 & 4 pp. 7-11). 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.

[1] The CASA definition varies slightly from the ICAO definition: *A computer programme designed to predict crewmember fatigue levels, based on scientific understanding of the factors contributing to fatigue. All bio-mathematical models have limitations that need to be understood for their appropriate use in an FRMS. An optional tool (not a requirement) for predictive fatigue hazard identification (ICAO Annex 6, Part 1, Appendix 8, Section 2.1.)*

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

2.1.1. Comparisons of work schedules

BFMs 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. 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.

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.

2.1.2. Identification of vulnerabilities within schedules

BFMs 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 fatigue-risk management actions.

2.1.3. Evaluation of rosters that extend beyond prescriptive limits

BFMs, 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. Specifically, BFMs 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. This particular application may be of use to both aviation schedulers, and to regulators in assessing the suitability of newly proposed roster patterns.

2.1.4. Optimising crew pairings and bid lines

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.

2.2. Non-scheduled / Irregular Operations

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

2.3. Work / Rest Cycles in Augmented Crew

BFMs 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.

2.4. Light Exposure and Napping Countermeasures

Another potential application of BFMs is to evaluate the opportunity for countermeasures such as light exposure[2], at-home sleep timing or napping to reduce the effects of fatigue. Exploratory scenarios may be evaluated through BFMs to test the potential impact of various countermeasures on fatigue risk and provide guidance on which countermeasures to implement, and when to use them.

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 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.

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. 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.

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. For instance, the use of a

[2] Please note that the only model sophisticated enough to evaluate the effects of light is the Kronauer-Jewett Interactive Neurobehavioral Model (INN). The INN was evaluated in the 2010 CASA paper, but excluded from the 2014 CASA paper *'as it is more applicable for research purposes and is not currently available for operational use* (in aviation environments).*'*

biomathematical model was seen as very useful to determine the optimal rest distribution and timing among crews in Ultra Long Range (ULR) flights.

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.

2.5.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 BFMs 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 has quite high accuracy in predicting individual sleepiness and sleep timing.

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, and for both predicting sleep quality and monitoring sleep quality 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.[3]

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 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. 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

[3] Please note that there are potential challenges to putting additional technology in the cockpit.

fatigue model individualisation approaches may contribute to enhanced individual fatigue prediction in the future. For example, if fatigue or task error measurements and sleep monitoring data were available for specific individuals, then programs for providing individualised fatigue predictions 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.

2.6. Training

A key focus in managing fatigue risk in operational contexts is education, specifically, education about the effects of fatigue[4], the causes of fatigue, the importance of effective sleep and good sleep habits, and the appropriate use of fatigue countermeasures. One school of thought is that all aviation industry personnel, including supervisors, crewmembers and scheduling staff, should be provided with education on these topics under an effective FRMS. 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.

BFMs 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 BFMs 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.

By demonstrating how variations in sleep duration, sleep times, nap timing and duration and other fatigue countermeasures alter fatigue risk, BFMs can be used to educate people on the dynamics of the sleep regulatory system and its effects on fatigue. The changes in fatigue risk over time may be counter-intuitive and 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 safety risks to organisations.

2.7. Safety Investigation

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 or analysing a person’s

[4] Including the role of circadian rhythms.

fatigue level at a specific time based on analysis of their prior sleep. 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 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] or similar observational methods).

3. Cautions on the use of Models

(Refer CASA, 2014, Biomathematical Fatigue Models Guidance Document, Section 2.2: Cautions on the use of Biomathematical Models p12)

3.1. Better for comparing scores rather than compliance with a threshold

BFMs 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.

3.2. Fatigue score limits must be validated

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.

3.3. Should not be used in isolation or as a go/no go criteria

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 BFMs 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.

3.4. Continuous improvement

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.

4. Limitations of Models

(Refer CASA, 2014, Biomathematical Fatigue Models Guidance Document, Section 2.1: Regulatory and FRMS context p11)

BFMs have limitations 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 BFMs 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.

(Refer CASA, 2014, Biomathematical Fatigue Models Guidance Document, Section 4: Limitations of Biomathematical Models pp18-22)

This section provides a detailed discussion of the limitations of biomathematical fatigue risk models which include:

- Models predict fatigue levels, which are not necessarily correlated with safety risk.
- Models consider only the acute effects of work schedules and not chronic effects, and may underestimate risk.
- Models predict average fatigue levels for a population and do not consider individual variability.

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. 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.

Consider 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 are 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. Likewise, the performance of sleep-deprived subjects is poorer than that of non sleep-deprived control groups, although there is 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, after correcting for exposure, accident and injury propensity reaches a rather earlier maximum at about midnight. 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.

A recent comprehensive review investigated the significant body of research linking fatigue and safety outcomes in detail. It was 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. The review first looked for evidence of the effects of various fatigue related inputs (circadian, sleep homeostasis and task-related influences) on fatigue and safety outcomes, then examined the evidence for each of these influences on performance capability, before finally summarising evidence for the link between performance and safety outcomes.

There is 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. 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). These operational defences or barriers are used by aircrew as protection strategies against the detrimental effects of fatigue. The use of these strategies could explain the non-linear relationship between safety-related indicators and fatigue-related indicators.

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 line of evidence is the chronic impact of work schedules on performance capabilities. One study 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. A subsequent study 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 a cross sectional study of a large sample of male industrial workers found cognitive deficits among those who had been exposed to shift work, when compared to those with no exposure. The study 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.

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. 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.

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. 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 BFMs 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.

A review was conducted of the association between a wide range of demographic factors and the risk of involvement in road accidents. It should be noted that it 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[5]. 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,* 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, and there is, for example, virtually no evidence that this relates to adjustment to circadian disruption or 'jet-lag'.

There are also a wide range of individual health problems, including, but not confined to, sleep disorders, that may impact on fatigue and safety. These problems were recently reviewed, again in

[5] No aviation variables have been identified that are sensitive to sleep loss and fluctuations in circadian rhythm; however measures have been identified in road transport (truck driving).

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.

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. Conclusion

As stated in the introductory section of this document, the purpose of this paper was to create a condensed version of the *CASA Biomathematical Fatigue Models Guidance Document*, focusing on the applications, limitations and cautions on the use of BFMs. As discussed above, BFMs can be useful tools to assist with the identification and management of fatigue hazards, but they should only be considered as one element of a comprehensive FRMS.

For further information, including the science behind fatigue modelling, model characteristics and structure, a summary of seven biomathematical fatigue models and model comparisons, analysis and conclusion, please refer to the full CASA document.

6. References

CASA, 2010, Biomathematical Fatigue Modelling in Civil Aviation Fatigue Risk Management: Application Guidance

CASA, 2014, Biomathematical Fatigue Models Guidance Document