Safety Regulation Group

CAA PAPER 2005/04

Aircrew Fatigue: A Review of Research Undertaken on Behalf of the UK Civil Aviation Authority

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Executive Summary

This report reviews the programme of work related to the sleep and wakefulness of the airline pilot that has been carried out by QinetiQ and its predecessor organisations (Defence Evaluation and Research Agency [DERA], Defence Research Agency [DRA] and RAF Institute of Aviation Medicine) for the UK Civil Aviation Authority (CAA).

Some early studies of the sleep patterns of aircrew on long-haul and round-the-world operations were carried out prior to the publication of the first edition of Civil Aviation Publication 371 (CAP 371) in 1975. However, the main programme of work was begun in the 1980s with an international collaborative study, co-ordinated by the National Aeronautics and Space Administration (NASA), into the sleep and alertness of pilots on layover after long eastward and westward flights. This was followed by studies of the polar route between London and Tokyo via Anchorage, and several studies of the in-flight sleep of crews on augmented flights.

The methodology for this early work was based mainly on recordings of the electrical activity of the brain (EEG) of the pilots while they were sleeping either in their hotel on layover or in the bunk facilities on board the aircraft. From these, it was possible to establish the nature of the subtle changes in sleep that occurred in response to the time zone transitions and to the accumulation of a sleep debt associated with the flights. The disruption of sleep was much greater after the eastward than after the westward flights, with shorter and more frequent periods of sleep on layover.

Investigations were also carried out into the pattern of circadian adaptation after long time zone transitions, although, for practical reasons, these mostly used non-aircrew volunteers. The results indicated that re-adaptation after an eastward flight was achieved more slowly than after a westward flight. However, after a 10-hour eastward transition it was observed that some individuals adapted by a phase advance and some by a phase delay. Some took over a week to resynchronise their body clock with local time, and all experienced reduced levels of alertness for up to 6 days after the flight.

At the same time as these studies were being completed for the CAA, QinetiQ was developing an alertness model based on laboratory simulations carried out for the Ministry of Defence (MOD). It was realised that this model was capable of providing initial estimates of the alertness of civil aircrew. Accordingly, information already collected on the sleep and circadian rhythms of aircrew was incorporated into the basic model to produce a proof-of-concept prototype of a computer program for the automatic assessment of airline rosters. This program was subsequently given the acronym of SAFE (System for Aircrew Fatigue Evaluation).

At this stage, the main thrust of the research programme changed, and it was agreed that any further work undertaken in support of the CAA's fatigue evaluation programme would also be used to validate the SAFE program. Accordingly, a series of studies was begun into the alertness of aircrew in flight. Instead of collecting EEG data on a relatively small number of pilots, subjective data were collected from a far greater number. In this way, it was much easier to identify general trends and to detect differences due to individual factors. The subjective data, mainly collected via diaries that the aircrew completed throughout a duty schedule or over consecutive schedules, were sometimes supplemented by activity monitors and by performance testing via small hand-held computers carried on the flight deck.

A large number of both short and long-haul flights have used this methodology. Among the long-haul flights studied were those by Britannia crews on the Haj operation. This operation, which was monitored over three consecutive years, was especially interesting since it was flown round the clock, with the same pattern of duty repeated at all times of day. In addition, since the nature of crew augmentation varied from year to year, and even within a particular year, it was possible to compare levels of alertness after sleeping in a bunk, after sleeping on the flight deck and after no sleep on an unaugmented flight. Other long-haul studies have included the London-Sydney route via Bangkok, and the Dubai-Perth route.

Three main short-haul studies have been carried out, involving crews from KLM UK, bmi and Britannia Airways. From the analysis of the data collected, it has been possible to establish the separate effect of the various factors that contribute to fatigue. These include time of day, time on duty, the number of sectors flown, early report times and the number of consecutive flights. Where appropriate, the trends observed in these factors have been incorporated directly into the model.

In addition to these field studies, investigations into two areas have been carried out in the laboratory. One of these was concerned with sleep inertia, and it identified the extent of the impairment in alertness that is likely to occur immediately following short periods of sleep either on the flight deck or in a bunk. The other was concerned with the impairment of sleep that can arise when aircrew attempt to rest in a hotel room during the day and are exposed to disturbances due to light and noise.

As more information was collected it was possible to develop the SAFE model to represent more closely the experiences of the aircrew. A beta version of the SAFE program was produced in May 2001, and distributed widely within the airline industry. Based largely on the feedback received, a modified version was released in March 2003 for evaluation by the CAA. Further changes have been made to improve the user interface and to incorporate data from more recent studies.

In its present form, SAFE can provide a valuable addition to the tools available to the regulator for the assessment of aircrew rosters. This has been demonstrated by its contribution to the evaluation of the requirements for crew augmentation in the new generation of ultra-long-range aircraft. There are still some areas of uncertainty, many of which it should be possible to resolve fairly rapidly. In addition, the model would be much improved if it were adapted to incorporate individual variability, instead of predicting only mean levels of alertness. The possibility of relating the output of the model directly to accident risk should also be considered.

Aircrew Fatigue: A Review of Research Undertaken on Behalf of the UK Civil Aviation Authority

1 Introduction

1.1 Terms of Reference

This report reviews the programme of work related to the sleep and wakefulness of aircrew that has been carried out by QinetiQ and its predecessor organisations for the UK Civil Aviation Authority (CAA).

1.2 Background

It has long been recognised that fatigue, sleep loss and circadian disturbance can degrade performance and safety and that this is an issue for many who work irregular hours. A considerable amount of research has been carried out on the performance of shift workers, with emphasis on such issues as the effect of speed and direction of rotation, the number of consecutive nights and the comparison between 8 and 12-hour shifts. However, it is difficult to apply many of the results directly to transport workers, whose patterns of work tend to be irregular and subject to last-minute changes and unexpected delays. In addition, the long-haul pilot is subject to further disruption from the effect of time zone changes and the lack of adaptation to the local environment.

To protect operations against the risk of aircrew fatigue, the CAA introduced, in 1975, guidelines for the avoidance of fatigue in CAP 371. This publication was based on the recommendations of the Bader Committee, and incorporated the scientific knowledge that was available at that time. However, this knowledge was extremely limited and the CAA has subsequently sponsored an on-going programme of research, which has been reflected in subsequent editions of CAP 371, in 1982, 1990 and 2004 [1]. The purpose of this report is to summarise the work that has been carried out under the research programme.

1.3 The Role of QinetiQ

The primary contractors for the fatigue research work have been QinetiQ and its predecessor organisations (until 1994, the RAF Institute of Aviation Medicine (IAM); until 1995, the Defence Research Agency (DRA); and until 2001, the Defence Evaluation and Research Agency (DERA)).

QinetiQ has a long history of research into sleep, performance and fatigue. In the early days, as the IAM, it undertook many investigations for the Ministry of Defence (MOD), including simulations of irregular patterns of work over several consecutive days, at its sleep laboratory at Farnborough. Other studies that required an isolation facility were contracted out to the University of Manchester. The experience and the knowledge gained from these and more recent studies have informed the CAA programme throughout its duration.

QinetiQ also has close connections with many other organisations and institutes engaged in research into aircrew fatigue, and has carried out a number of collaborative studies as part of this programme of work. These organisations include the National Aeronautics and Space Administration (NASA), Deutches Zentrum für Luft- und Raumfahrt (DLR), Nederlands Instituut voor Toegepaste

Geowetenschappen (TNO), the Karolinska Institute Stockholm, the University of Paris and the University of Auckland.

Scientists from the four European organisations mentioned above form, together with QinetiQ, the membership of ECASS (European Committee for Aircrew Scheduling and Safety). This committee was established in 1994 to provide an impartial source of advice to the airline industry within Europe on all matters relating to aircrew fatigue.

1.4 Overview of the Report

The objective of this report is to provide a brief summary of the work on aircrew fatigue that QinetiQ has carried out in the course of this programme. The intention is not so much to describe every single study, although most are mentioned at least in outline, but to provide an indication of the main thrust and purpose of the research.

Although a small amount of work was carried out before the publication of CAP 371 in 1975, the main work began in the 1980s with a series of investigations into the sleep of aircrew both on layover after a time zone transition and in the crew rest facilities provided on augmented flights. These early studies are described in Section 2.

In Section 3, the QinetiQ Alertness Model is described. This was being developed for the MOD independently of the aircrew studies, but it was soon realised that it could provide the basis for predicting alertness levels associated with different aircrew rosters. This led to the development of the first prototype of SAFE (System for Aircrew Fatigue Evaluation), described in Section 4.

The SAFE model was immediately recognised as a possible means of applying objective assessment to rosters rather than the largely subjective methods that were generally used by the regulatory authorities. Accordingly, considerable effort was put into the validation of the SAFE model, and it is this process that is the main subject of this report. Section 5 describes the alertness studies that have been carried out in support of this activity, Section 6 describes the on-going validation and in Section 7, some of the main areas of remaining uncertainty are highlighted. Finally, in Section 8, the current position with respect to the computer model is described and issues relating to the way forward are discussed.

2 Early Sleep Studies

2.1 Sleep Patterns

Initial work, in the late 1960s, was concerned with the sleep patterns of aircrew on long-haul flights with the Boeing 707. The first study was based on the sleep pattern of a single airline pilot operating long-haul east-west routes over a period of 18 months [2]. The flights consisted of western (transatlantic) return schedules, eastern return schedules and round-the-world schedules. The individual schedules themselves were completed between six and 16 days.

Perhaps the most interesting finding from this study was the extent of the irregularity in the pattern of sleep. The distribution of sleep duration is shown in Figure 1. The duration of only one in three of the sleep periods during route flying was within the range (5.8 to 8.0 hours) of those observed during a period of non-flying duty. One in four of the sleep periods was a nap of two hours or less (the large majority less than an hour), 22% were short sleeps of between two and five hours, and 19% were very long sleeps of between eight and 11 hours. This irregularity was a consequence of both the irregular duty periods and the adaptation to the time zone changes.

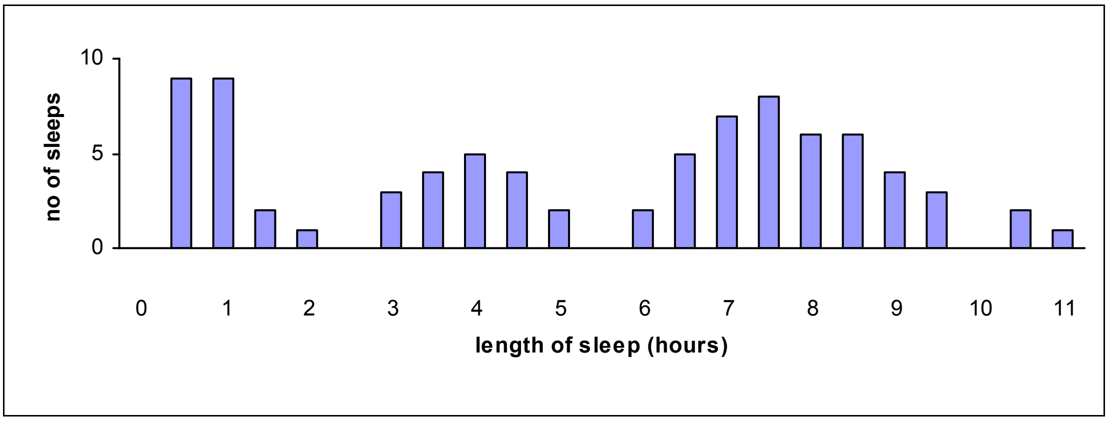


Figure 1 Histogram of Duration of Individual Sleep Periods during Route Flying

Overall, the average sleep per 24 hours during route flying was similar to that during non-flying duty. It was therefore concluded that the predominant problem related to sleep on this type of route was the disturbance of the normal sleep pattern rather than sleep loss. However, at the time the study was carried out, the physiological problems associated with this type of schedule were not understood.

Although sleep loss was not identified as a major problem, there were occasions during the schedule when the average amount of sleep per day, over a 72-hour period, fell below normal. Plots of average sleep against the rate of working suggested that this transient sleep loss was unlikely to occur if the rate of working was below a level that depended on the days on route [3]. It was concluded that the workload compatible with an acceptable sleep pattern reduces, possibly in a logarithmic manner, as the number of days of the schedule increases. The curve defined by this relationship was subsequently named 'the Nicholson Curve' after its author. It limits the number of flying duty hours to 50 in seven days, 72 in 14 days and 120 in 28 days. The Nicholson Curve, although not part of the SAFE model, can be called up from the SAFE program.

2.2 International Collaborative Study

No further work on civil aircrew was carried out until the mid 1980s, when the RAF Institute of Aviation Medicine (IAM) agreed to participate in an international collaborative study of layover sleep and alertness [4]. This was the first time that the sleep of aircrew on layover had been monitored with electroencephalographic (EEG) recordings in their natural environment. In addition, the alertness of the crews was monitored throughout the layover period using the Multiple Sleep Latency Test (MSLT).

Crews from four airlines participated. British Airways and Lufthansa crews flew westward to San Francisco (SFO) from either Frankfurt (FRA) or London (LHR). Crews from JAL flew eastward to San Francisco from Tokyo (NRT), while Pan Am crews based in San Francisco flew either eastward to London or westward to Tokyo. The duration of the layover periods was approximately 48 hours, with the exception of the NRT-SFO route, for which it was approximately 24 hours. The time zone differences were seven, eight or nine hours. The aircraft were all Boeing 747 Classics.

The results from each airline were highly consistent, and a clear difference emerged in the patterns of sleep following eastward and westward flights. After a westward flight, crews tended to delay their sleep until nearly their normal time of day [5]. The resultant sleep deficit led to shorter sleep onset times and good quality sleep in the first part of the night. However, there was increased wakefulness in the second half of the night as the crews tried to sustain their sleep beyond the normal waking time according to their body clock. Sleep patterns were much more variable and fragmented after eastward flights, as individuals attempted to shorten their day, and this was reflected in subsequent levels of daytime drowsiness.

2.3 The Polar Route

In the late 1980s, two studies were carried out of aircrew undertaking the polar route between London and Tokyo. This was a more complex schedule than those studied previously, since the eight-hour eastward transition was accomplished by two westward flights, with a 24-hour layover in Anchorage on both the outward and return legs.

In the first study [6], sleep logs were completed by 34 pilots on schedules that involved a one, two or three-day layover in Tokyo. The schedules therefore covered five, six or seven days, and the flying duty periods (FDPs) for the seven-day schedule, in which pilots flew from Tokyo to Osaka (OSA) on the fourth day, and returned via Osaka, are shown in Figure 2. The aircraft were Boeing 747-400s.

Information was collected starting from the night before the outward flight, and ending after the end of the second full night following the return. A histogram of the duration of the individual sleep periods throughout this time is given in Figure 3. The sleep pattern was even more variable than in the earlier Boeing 707 study, with only 28% of all sleeps between six and nine hours. The peak values correspond to short naps (sleeps of less than one hour duration), short sleeps (between three and four hours) and sleep periods of normal duration. Nine per cent of all sleeps were 10 hours or longer, with one reported at over 16 hours. In general, the shorter schedules showed greater variability.

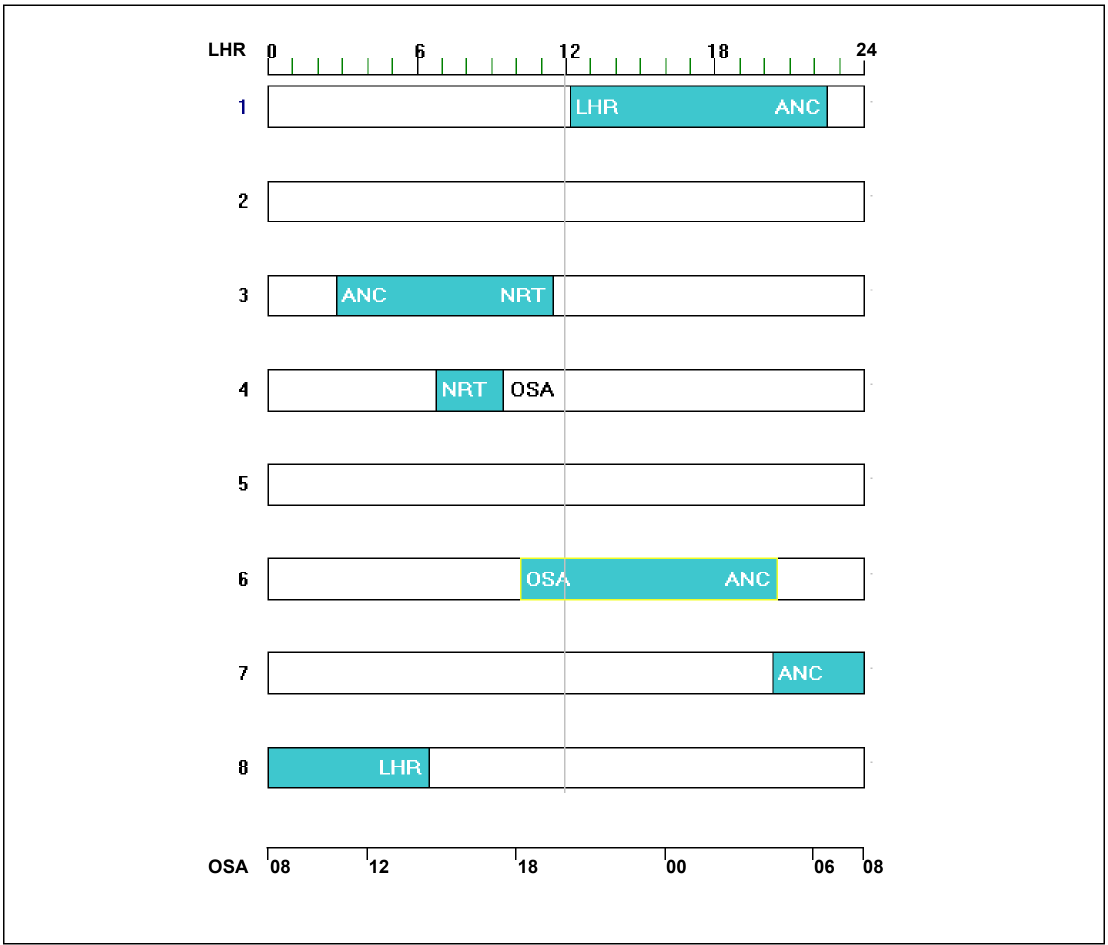


Figure 2 Flight Schedule for the Polar Route (7-day schedule)

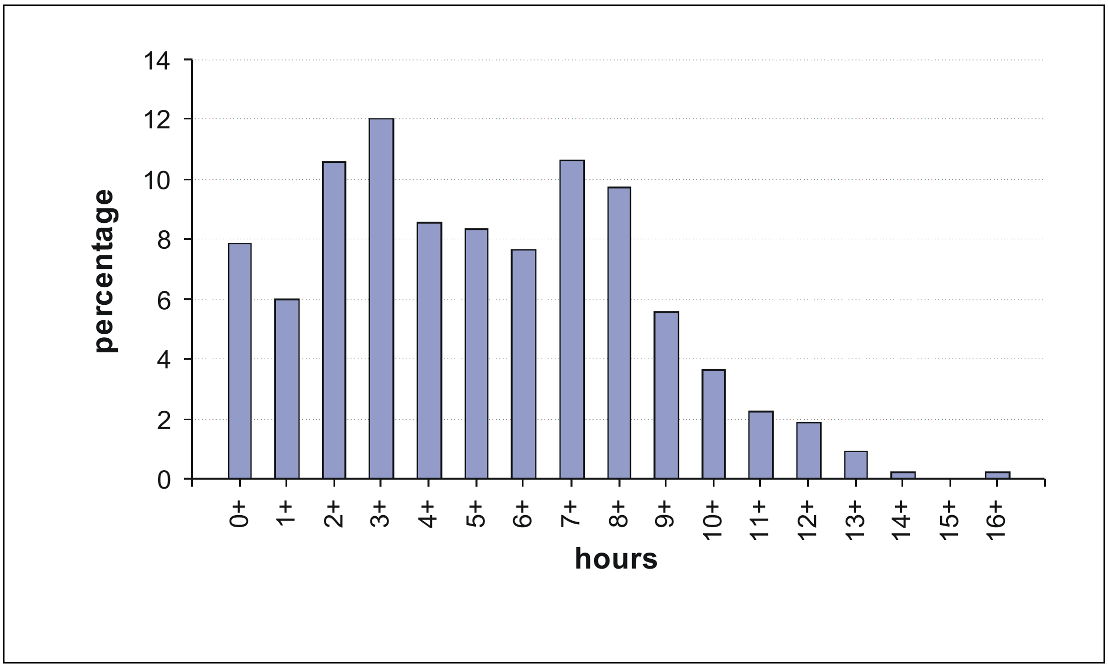


Figure 3 Reported Incidence of Sleeps of Various Durations During the Polar Schedule

On return to the United Kingdom, the sleep disturbances were more severe and systematic than during the trip and, in some cases, these persisted until the second night after the return, when reporting ended.

The second study involved a more detailed investigation of sleep and alertness of 12 aircrew (three on each of four trips) before, during and after a seven-day polar schedule [7]. EEG recordings of sleep were made of all layover sleeps, and they continued for 10 days after the return to the United Kingdom. Throughout the study period, rectal temperatures were recorded at four-minute intervals, and subjective alertness was assessed every two hours whilst awake using visual analogue scales.

It was difficult to establish reliable estimates of the temperature rhythm during the trip itself, owing to the low amplitude of the rhythms. However, the changes in acrophase on recovery (Figure 4) suggested that the rhythms of three aircrew were delayed by more than nine hours with respect to local time on return, and that two of these readapted by a phase delay and one by a phase advance. The seven whose rhythms were delayed by less than nine hours, all readjusted by a phase advance. They included all three who were delayed on the return leg and spent an extra day in Anchorage. Of the remaining two, the rhythm of one never drifted far from home time, while the amplitude of the rhythm of the other was too low to permit a reliable estimate of acrophase (a measure of the extent and timing of change within a cycle of the circadian rhythm).

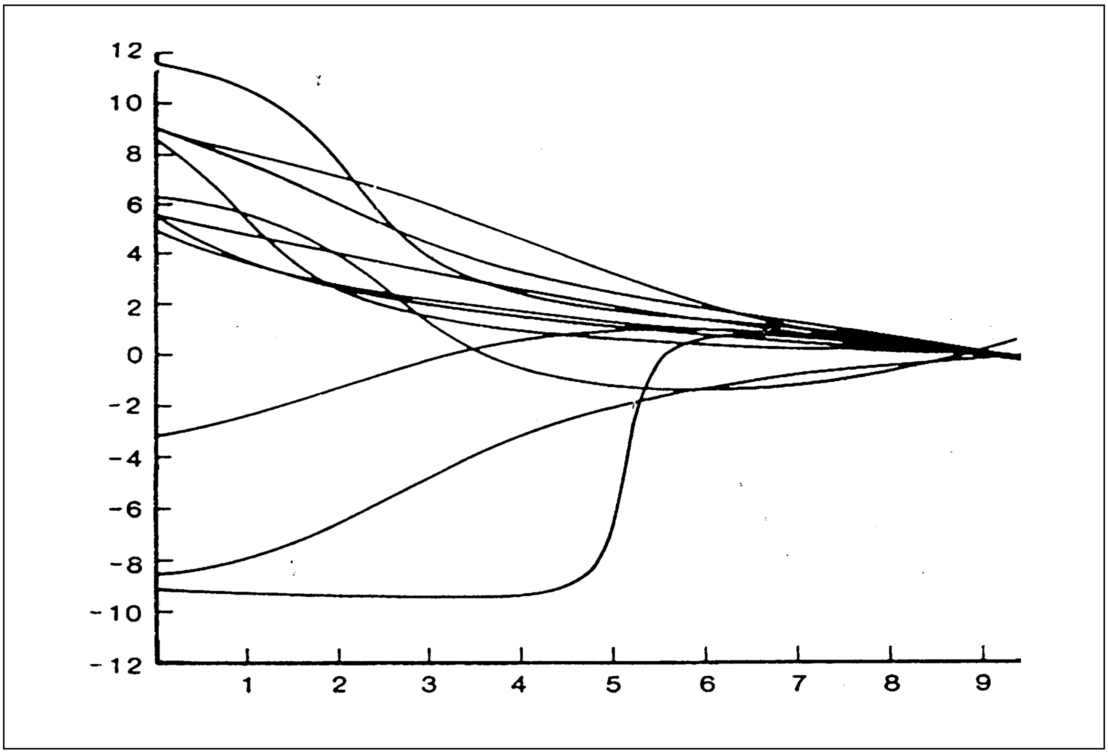


Figure 4 The Acrophase of the Circadian Rhythm of Temperature on the Return from the Polar Schedule

There were changes in the nature of sleep during the trip, and these were related to a combination of factors. The loss of sleep generated by the outward journey gave rise to a rapid sleep onset in Anchorage, and to faster sleep onset, fewer awakenings, and earlier and increased slow-wave[1] activity on the first night in Japan. The reduction in REM sleep on the second night in Japan, and the subsequent increase in REM sleep in Anchorage on return probably reflected the shift in the circadian rhythm. The propensity for REM sleep is known to be related to the circadian phase, but the significance of the transient loss of REM is not fully understood.

On the first night after the return, six out of the 12 individuals slept over an hour less than on baseline, and this included one sleep period of less than three hours. The proportion that slept over an hour less than on baseline dropped to three out of 12 on the second recovery night, and one or zero on each remaining night. There was a marked increase in total sleep time on the fourth night, together with a surge in total REM sleep. Moreover, there was a steady increase in subjective levels of alertness over the first five days after the return.

The overall conclusion was that the polar route was associated with extensive disruption of the sleep-wake and of the circadian system, and that it took approximately five days for the crews to make a complete, or almost complete, recovery.

1. For a brief description of the sleep process, including slow-wave and REM sleep, see Appendix A.

2.4 Sleep in a Bunk

2.4.1 Questionnaire Study

With the introduction of long-range aircraft such as the B747-400, non-stop flights became possible which extended duty periods beyond those defined by existing flight time limitations. To manage the fatigue implications of these extended duty periods, rest facilities in the form of a separate compartment containing bunks were installed so that crews could take some rest in-flight. Depending on the length of the flying duty period, crews were augmented by either one or two pilots. Rest away from the flight deck was taken in rotation, and duty periods were extended as a factor of the duration of the in-flight rest period. During the 1990s a series of studies was completed on board the B747-400 aircraft, which investigated the quality and quantity of sleep in the rest facility and strategies for managing rest.

The first investigation involved a survey of 255 British Airways pilots [8]. The data were collected from a total of 851 flights on the B747-400, consisting of return trips between London and a variety of destinations, the majority of which were to the Far East. Crews reported the duration and quality of their sleep, the length of the rest period, and their levels of alertness at the start and end of the rest period. In addition, details of factors that disturbed sleep were also requested.

The timing of the rest periods in relation to the circadian rhythm and the duration of wakefulness affected the quality and quantity of sleep and alertness. Estimates of the duration of sleep in-flight ranged from 0 to 6.5 hours (mean 2.22 hours) and it took on average 0.77 hours to fall asleep. Alertness after sleep was positively correlated with the duration of sleep, irrespective of the level of alertness before sleep, though the relationship was more marked when alertness before sleep was low. Factors that disturbed sleep were reported to be the ambient noise of the aircraft, random noise, turbulence, the dry atmosphere, inadequate bedding, not being tired and having thoughts on the mind. Both sleep quality and alertness after sleep were reduced by turbulence and random noise.

Some years later, the data from this study were re-analysed to determine the factors related to the schedule that influenced the amount of sleep that pilots managed to achieve, and the results were incorporated into the SAFE program. The two most important factors were the time of day and the length of the time available for rest. Trends in the length of sleep at a range of different times of day, calculated from the best fitting regression model, are illustrated in Figure 5. This figure relates to late departure times (after 17:00). Less sleep is obtained when the departure time is earlier.

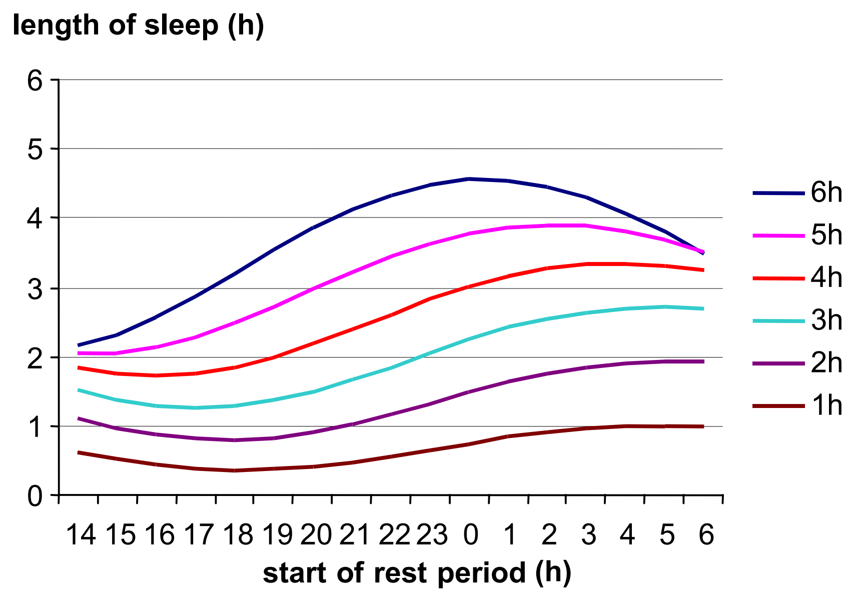


Figure 5 Model of Sleep Duration as a Function of the Length of the Rest Period

Whilst the survey provided a subjective overview of how pilots were sleeping in the bunk it was important to collect objective data to substantiate these findings. Using electroencephalographic techniques three further in-flight studies were carried out. They are the subject of the following sections.

2.4.2 **In-flight Studies: London to Johannesburg and Tokyo**

Initially two routes were chosen, the first of which was between London and Johannesburg (JNB) and the second between London and Narita (NRT - Tokyo) [9]. The two schedules included flights of similar duration, similar layover and crew composition but the time of departure and direction of travel differed. Those flights to and from JNB departed in the early evening and involved minimal time zone change (at the time of the study +1h relative to BST) whilst those to NRT involved an early afternoon departure and a time zone change of +9h (GMT).

Twelve pilots took part in each study (4 x 3-man crew). Sleep was recorded electroencephalographically and environmental parameters (noise, temperature, humidity and turbulence) were recorded in the bunk compartment. In addition, sleep was recorded prior to departure during a baseline night in the laboratory at Farnborough, during the two local nights of the layover and on return to the UK. Participants chose their own pattern of sleep and wakefulness throughout the schedule.

The pattern of sleep during the two schedules is shown in Figure 6 and Figure 7. The boxes indicate sleep episodes and those shown in red represent episodes of in-flight sleep.

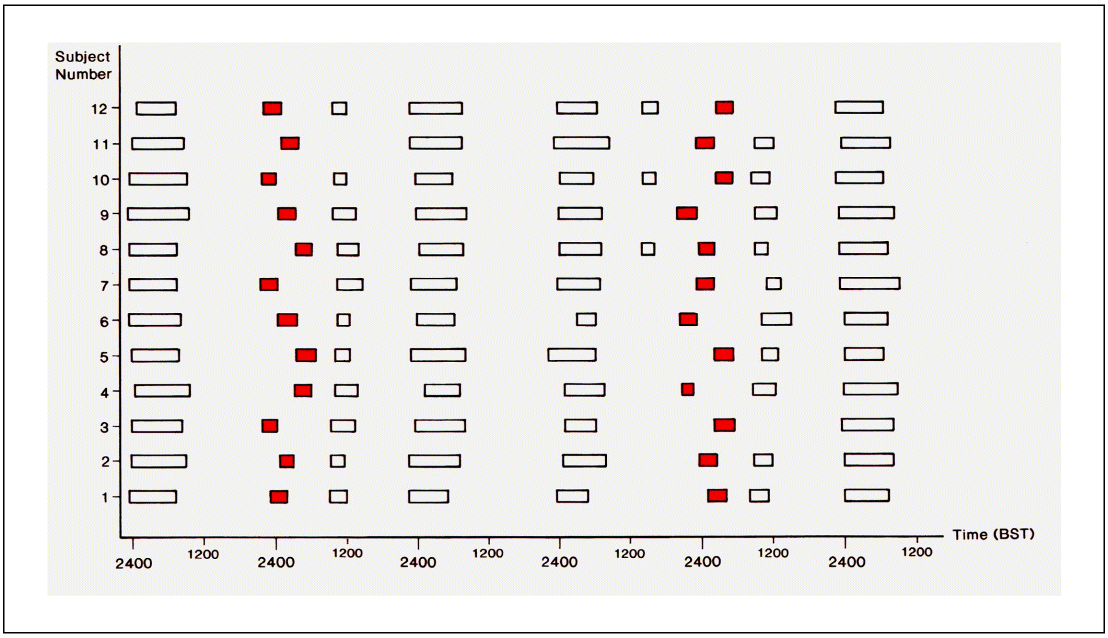


Figure 6 Pattern of Sleep during the Johannesburg Schedule (in-flight sleep are shown in red)

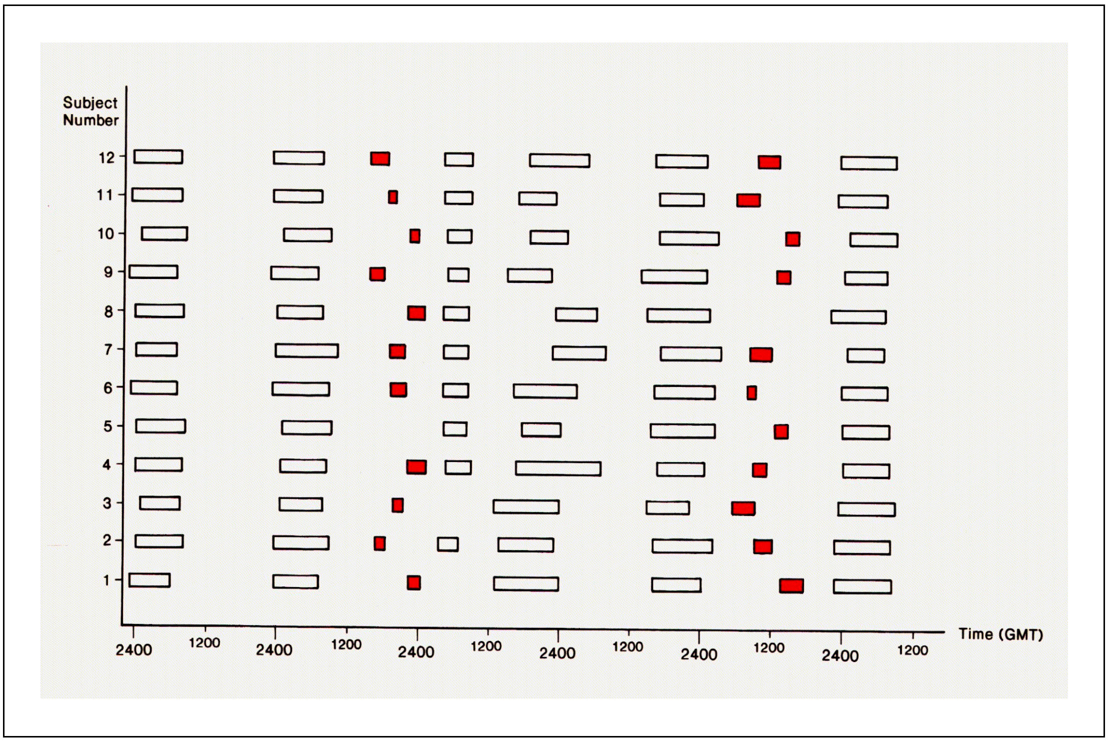


Figure 7 Pattern of Sleep during the Narita Schedule (in-flight sleep are shown in red)

In JNB most participants chose to take a short nap after the overnight flight and slept during the local night for each of the two nights of the layover. Three pilots took a nap during the early afternoon before the return flight and most took a further nap on arrival back in the UK.

On arrival in NRT, most individuals chose to nap. However, there was more variation in the timing of sleep on the first night in NRT than in JNB. At the extremes, two pilots remained close to GMT, while two other participants, who did not nap on arrival, adopted local time. The timing of sleep was more homogenous on the second night with individuals retiring to bed between 23:30 and 02:00 (local time). During the outbound flight one subject who was scheduled to rest first did not attempt to sleep and one failed to fall asleep during the second rest period. Similarly, during the return flight, one individual did not attempt to sleep during the first rest period and another did not sleep during the third rest period.

The quality and quantity of in-flight sleep was influenced by the timing of the flight and also by the scheduling of rest periods within the flight. Total sleep time during the overnight flights on the JNB route was greater than that obtained during the NRT flights. In addition, sleep was better during the later rest periods on the JNB flights. There were significant differences in noise levels, temperature and humidity between and within flights, but correlations between these factors and sleep were not established, possibly due to the limited amount of data. These studies indicated that while it is possible to obtain adequate in-flight rest, the scheduling of rest periods requires careful consideration, particularly for the relief crew.

2.4.3 In-flight Studies: London to Seoul

In a subsequent study, two strategies for the scheduling of in-flight rest were compared [10]. One strategy involved both the main and relief crew taking a single long rest period. For the other, crews alternated in the rest facilities, with each pilot taking two shorter rest periods.

Twenty-eight aircrew, selected from the British Airways B747-400 fleet, undertook a return trip from London to Seoul. Sixteen aircrew (4 x 4-man crews) took a rest period of approximately six hours and twelve aircrew (3 x 4-man crews) had the opportunity to rest during two shorter periods of approximately three hours each. As in the previous two studies, sleep was recorded electroencephalographically and temperature, humidity and noise levels were monitored whilst crews slept in the bunk.

During the outward trip, the majority of those who were scheduled two rest periods chose to go into the bunk compartment on only one occasion, four out of 12 sleeping during their first rest period and 10 out of 12 during the second. All who were scheduled to have a long rest period attempted to sleep at some time during the allotted period, although one individual failed to sleep at all during a rest period early in the flight.

On the return trip, all those taking one rest period succeeded in sleeping. Of those scheduled for two rests, six out of 12 attempted to sleep during the first period, one of whom remained awake throughout. All 12 attempted to sleep during their second rest period, although one was unsuccessful and one slept for less than 10 minutes. The three individuals who slept little or not at all during one rest period, achieved reasonable sleep during their other rest period.

The average amount of sleep obtained when short rest periods were being operated was 36 minutes less than for a single long rest period (108 compared with 143.8 minutes). However, the reduction in sleep associated with the short rest periods did not apply during the first rest period on the outward trip.

Individuals were significantly more tired before the second long rest period than before the first or second short rest period. There were no differences on waking. However the increase in alertness was greater after a long rest period than after a short rest. Indeed the increase in alertness was correlated with the duration of sleep (Figure 8).

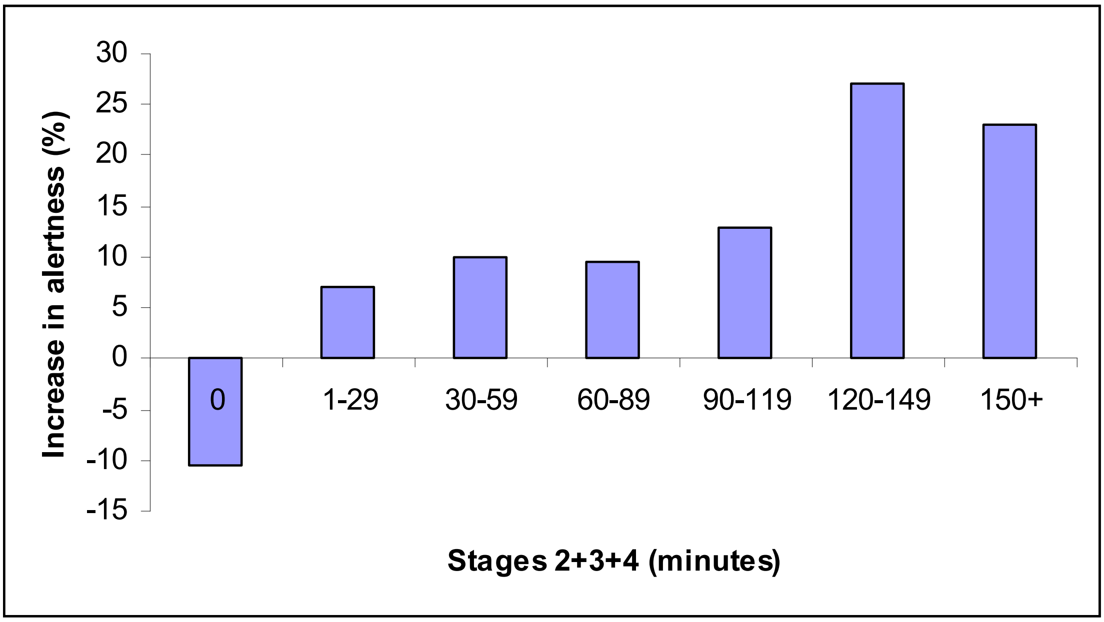


Figure 8 Changes in Subjective Alertness with Increasing Amounts of Sleep

During this trip the requirement for good in-flight rest was greatest on the return leg, when the effects of the long flight were compounded by circadian desynchronisation and the disruption of sleep on layover. At times when the requirement for sleep was greatest (e.g. during the second part of the flight or when crews were unacclimatised), the quality of sleep was better and the duration longer during a single rest period of six hours than during two three-hour rest periods combined.

When the requirement for sleep was least (e.g. during the first part of the outward leg with a morning departure), a single six-hour period did not provide better sleep than two three-hour periods scheduled during the first and third quarters of the flight. Aircrew with two opportunities for sleep would have a better chance of obtaining at least some sleep during the flight.

At a much later date, simulations of the in-flight sleep of crews on augmented flights were carried out to determine the requirements for sleep during ultra long-range operations. These clearly indicated a preference for two rest periods on most flights of 16 hours or more.

3 The QinetiQ Alertness Model

3.1 Derivation

The first steps in the derivation of an alertness/fatigue model were taken in the late 1980s as part of a programme of work for the Ministry of Defence. At this early stage, this work was independent of the studies that were being carried out at the same time for the CAA, and it was only later that the relevance of the work to the civil sector was fully exploited. The model that was derived from these early studies came to be known as the QinetiQ Alertness Model.

In its initial form, the QinetiQ Alertness Model was based on a series of laboratory experiments [11] that investigated the effects of irregular patterns of work and rest on performance, during conditions of partial isolation. The experiments were specifically designed to provide irregular patterns of work and rest that avoided overall sleep deprivation. In addition, they permitted efficient estimates to be made of changes in performance at different times of day, during work periods of varying duration.

The experimental work was carried out at an isolation laboratory belonging to the University of Manchester. A total of 30 subjects followed an irregular schedule for a period of nine consecutive days. The schedule included work periods of six, 12 and 18 hours, which were balanced for time of day. These work periods were separated by rest periods of six hours, during which the subjects were able to sleep.

At intervals of two hours throughout the waking periods, performance was monitored on a variety of tasks, and subjective assessments of alertness were obtained. The tasks varied in the different experiments, with the exception of the Digit Symbol Substitution Task (DSST) [12] which was included in every experiment, and which was therefore used as the basis for the model.

A detailed description of the derivation of the initial model from these experiments is given elsewhere [13].

3.2 Description

The QinetiQ Alertness Model consists of two components, one related to the circadian rhythm and the other to the sleep-wake process. For the fully adapted individual, with sleep during the night and wakefulness during the day, these components may be associated with time of day and time since sleep respectively, as shown in Figure 9. As the analysis of the experimental data revealed no significant interaction between these two factors, they were combined additively in the model.

The time-of-day component represents the diurnal change in alertness from low levels overnight to a peak in the late afternoon. This variation is associated with the internal circadian rhythm or 'body clock' and normally remains entrained to the local time of day. However, the phase of the circadian rhythm can vary under the influence of time zone transitions or major changes in the sleep-wake pattern. There may also be transient changes in the amplitude of the rhythm. These changes were modelled by a forced van der Pol equation [14], the parameters of which were estimated from the Manchester experiments described above.

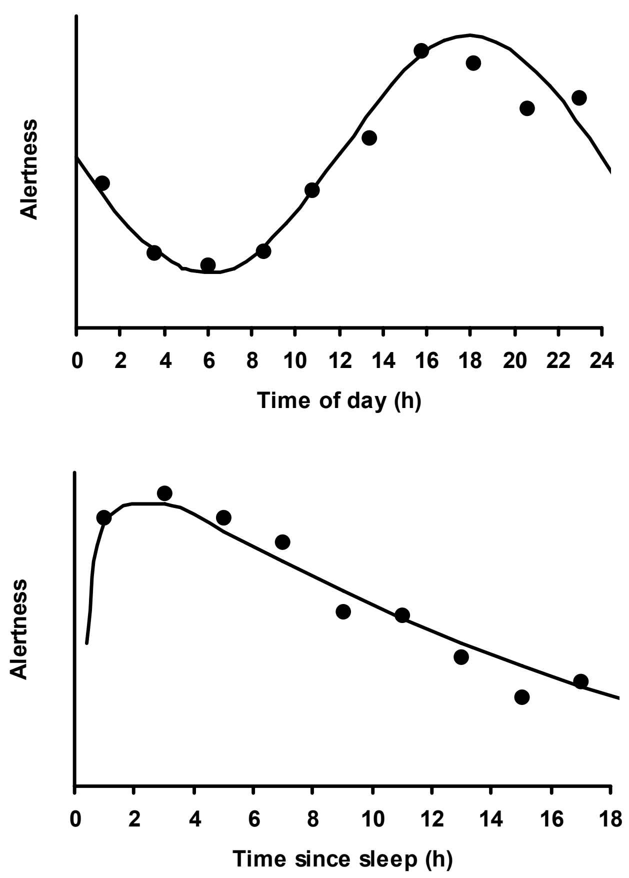


Figure 9 The Two Components of the Alertness Model (arbitrary scale)

The time-since-sleep component contains two separate elements, following the model of Folkard and Åkerstedt [15]. The first of these is the recovery of alertness immediately on waking: the 'sleep inertia' effect. The second component is the exponential reduction in alertness associated with increasing time since sleep and the corresponding exponential increase in alertness generated during sleep. This second component is modelled by the so-called 'S Process' [16], which represents the requirement for sleep as a function of the pattern of sleep and wakefulness. The S Process enables the model to estimate the differential influence on alertness of sleep periods of different lengths.

3.3 Output

The output from the model consists of levels of alertness on a scale from 0 to 100, where the limits represent the lowest and highest levels that are theoretically achievable.

The trend in alertness during duty periods at different times of day will generally be different. This is illustrated by Figure 10 which shows how the output of the model changes as a function of the time of day on waking and the duration of the waking period. In this figure, the assumption is made that the previous sleep is sufficiently long to ensure that the individual is fully rested on waking. When this is not the case, then alertness levels will be lower.

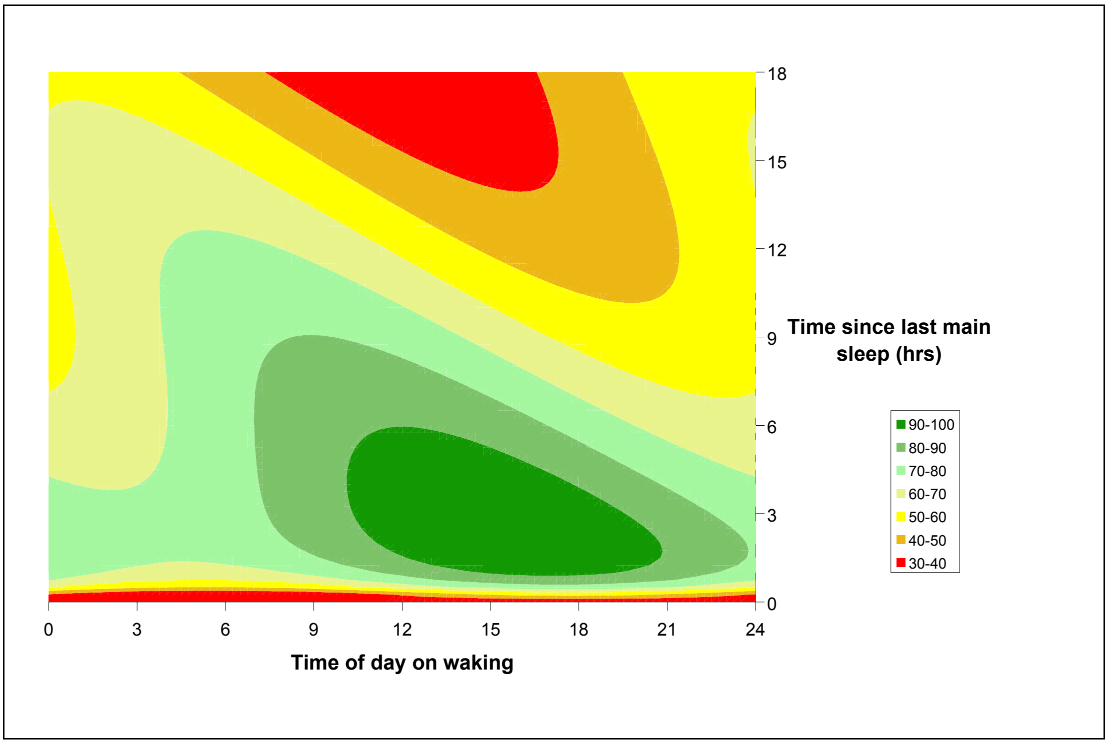


Figure 10 Changes in Alertness Following Sleep Periods at Different Times of Day

Figure 10 strictly applies to the duration of wakefulness rather than to the duration of a duty period. However, with the added assumption that an individual is fully rested at the start of a duty period, it can be directly related to levels of alertness during duty periods starting at different times of day. Of course, it may be necessary, in practice, to allow also for a period of at least an hour between the end of sleep and the start of duty.

With these assumptions, the information in Figure 10 can be used to predict the trend in alertness during duty periods starting at different times of day. Thus, for a duty period starting at 08:00, alertness remains at a relatively high level for over 12 hours. This is because the deterioration associated with time since sleep is counteracted by the rising circadian trend. However, when duty starts in the evening, the trend in both components is downward, and alertness falls rapidly after only a few hours.

3.4 Relationship with Performance

The final stage in the development of the QinetiQ Alertness Model was the derivation, in the late 1990s, of relationships between the output from the model and various measures of performance. This was achieved by a re-analysis of various studies that had been carried out at the sleep laboratory in Farnborough between 1990 and 1997 [17].

A database was established including information from seven experiments, which had been conducted either to simulate work patterns relevant to military operations or to investigate the effects of different types of medication. Results were collected on a wide range of tasks, including those designed to measure coding ability, visual vigilance, tracking, sustained attention and memory. In addition to these basic measures of performance, results were obtained from the multi-attribute task (MAT) battery [18]. This is a computerised representation of four tasks which aircrew are required to perform during flight. The tasks are run simultaneously and comprise system monitoring, tracking, resource management and auditory communications.

Relationships for performance as a function of the alertness model have been derived. Together with the alertness model, these equations may be used to predict changes in performance related to the timing of the duty periods and the sleep-wake cycle. Table 1 shows the predicted changes in performance after periods of 16 and 24 hours continuous wakefulness starting at 07:00. For example, the percentage missed on the continuous memory recall task increases from a baseline value of 5% to 5 x 1.76 = 8.8% after 16 hours and to 5 x 3.1 = 15.5% after 24 hours.

These results illustrate the differential impact of fatigue on different types of task. For a relatively simple task, such as visual vigilance, where normal response times are less than 0.5 seconds, the increase in response time is relatively small, even after 24 hours awake. However, the number of missed responses increases by more than twice after 16 hours and by more than four times after 24 hours. In contrast, in the more complex tasks such as the MAT battery, response times, which are normally greater than a second, increase by around 25% after 16 hours, and by over 70% after 24 hours.

The relationships between performance and alertness are illustrated in Figure 11 with respect to an unstable tracking task and the proportion of correct responses on a visual vigilance task. The confidence intervals shown on the graphs relate to the expected degradation from the level of performance at an alertness level of 80. The level of 80 was chosen as the point of reference as it corresponds approximately to the maximum level of alertness that would be predicted during a normal sleep-wake cycle.

Variable	**Baseline Performance**	**Decrement after 16h**	**Decrement after 24h**
Visual vigilance – response time (s)	0.43	x 1.06	x 1.13
Visual vigilance – % missed	16%	x 2.57	x 4.56
Continuous memory recall – response time(s)	0.46	x 1.16	x 1.41
Continuous memory recall – % missed	5%	x 1.76	x 3.10
Unstable tracking – RMS error	329	x 1.56	x 2.49
MAT battery – peripheral task 1 response time(s)	1.51	x 1.35	x 2.17
MAT battery – peripheral task 2 response time(s)	3.68	x 1.25	x 1.71

Table 1 Performance Decrements after Continuous Periods of Wakefulness starting at 07:00

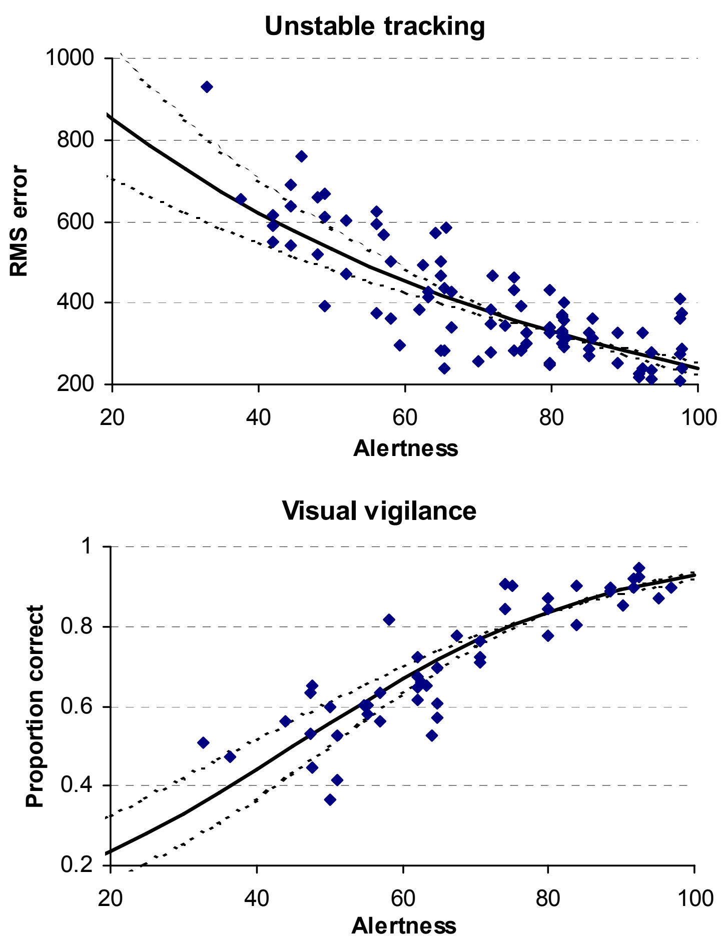


Figure 11 The Relationship between the Alertness Model and Two Measures of Performance

3.5 Equivalent Levels of Alcohol Intoxication

A relationship was derived between the performance decrements associated with reduced levels of alertness as predicted by the model, and those associated with alcohol intoxication. The information that was used to derive this relationship is described elsewhere [19]. It was based on an experiment in which the performance of subjects on a tracking task was measured on two separate days under two different conditions. In the first condition, they consumed 10 g of alcohol at 30-minute intervals from 08:00 until their blood alcohol concentration (BAC) reached a level of 0.1%. In the second condition, they were kept awake for 28 hours.

A relationship was derived in the form $z = -0.0455 + 0.194 \exp(-0.0198x)$, where x is alertness on the 100-point scale, and z is the equivalence percentage BAC. Thus an alertness level of 20 corresponds to a BAC level of 0.085%, which is just over the permitted level for drivers of road vehicles in the UK. This is approximately the level reached at 07:00 after 24 hours of continuous wakefulness.

4 Development of the SAFE Prototype

4.1 Background

With the development of the QinetiQ Alertness Model, the question arose of its applicability to civil air operations. Although it had been constructed from the results of laboratory investigations, the physiological factors that it incorporated were as relevant to aircrew as to any other group of individuals. The possibility was therefore considered of developing the model to the point where it could be used to reflect the fatigue and alertness levels of crews throughout any given roster. This might then provide an objective assessment of rosters that would at least complement the largely subjective methods generally used by regulatory authorities.

It was these considerations that led to the production of the SAFE program. Prior to the development of the initial prototype, further work was carried out to establish the influence of physiological factors that were particularly relevant to aircrew. This work was concerned with two main factors, namely circadian rhythms and sleep patterns.

With respect to circadian rhythms, more information was required on the rate of adaptation to the rapid time zone transitions to which long-haul pilots are frequently exposed. From an early study of non-aircrew volunteers, carried out for the Ministry of Defence, estimates had been obtained of the rate of adaptation to five-hour westward and eastward transitions [20]. The results confirmed the predictions of the model that circadian rhythms are generally able to adapt more rapidly to a westward shift that involves a phase delay, than to an eastward shift that involves a phase advance.

However, based on the model predictions, there was considerable uncertainty about the effect of very long transitions, particularly in an eastward direction. Therefore, two further studies were carried out, both using non-aircrew volunteers, one of a seven-hour eastward transition and one of a 10-hour transition. Both these studies are described in this section.

The second area where further information was essential was the influence of duty schedules on the sleep patterns of the crews. This was because the QinetiQ Alertness Model required the pattern of sleep as an input. It was therefore necessary, before it could be extended to the prediction of alertness throughout any given roster, for a sleep generator to be constructed. To obtain the information on which such a generator could be based, two studies were carried out, one of long-haul and one of short-haul crews. Both of these are described below.

4.2 Seven-hour Eastward Transition

In this study [21], 12 volunteer subjects completed a return trip between London and Hong Kong. The purpose was to determine the time that is required to adapt to a seven-hour eastward transition, and to investigate changes in sleep and alertness during the period of adaptation. The schedule consisted of a 72-hour baseline period prior to the outward flight, a continuous seven-day period in Hong Kong and, after two days off, a further two days in Hong Kong before the return flight.

The assessment of adaptation rates was based on continuous recordings of rectal temperature. After correcting for masking effects due to sleep and activity, it was established that nine subjects adapted by a phase advance and two by a phase delay (the data from the 12th subject were lost due to a problem with the recordings). However, there was a large variation between the subjects in the speed and pattern of resynchronisation, with some individuals requiring at least seven days to adapt.

The quality of sleep was poor on the first two nights in Hong Kong, with increased wakefulness, reduced REM sleep and lower levels of sleep efficiency. There was evidence of a recovery in REM sleep on the fourth night, after which sleep returned to normal.

On five occasions on each day after the flight, subjects were asked to carry out the digit symbol substitution task. Their performance on this task was not sustained at usual levels throughout the first two days in Hong Kong, with deficits on the first day already evident by 14:30. However, the only significant reductions in subjective alertness were during the day immediately following the arrival.

4.3 Ten-hour Eastward Transition

Simulations using the model suggested that eastward transitions close to 10 hours would be associated with the longest resynchronisation times, and that both the direction and pattern of the phase response would be highly sensitive to small changes in the model parameters. To investigate the effect of such a time zone shift on sleep quality and daytime alertness, a study was carried out of 12 volunteer subjects following a flight from London to Sydney via Bangkok [22]. Whereas the subjects in the Hong Kong study were young (average age 25 years), an older group (average age 41) was chosen for this study, to represent more closely the aircrew population.

The schedule consisted of a 48-hour baseline period prior to the outward flight, a continuous eight-day period on arrival in Sydney and, after two days off, a further two-day period before the return flight to London. As in the seven-hour study, subjects retired to bed at their normal time of day, and they were woken after 8.5 hours if necessary. Performance and subjective data were obtained during four 45-minute rest periods, starting at 09:15, 13:00, 16:15 and 20:00. Rectal temperature was recorded throughout the experiment.

The phase changes in the unmasked temperature after the arrival in Sydney are shown in Figure 12. There were large individual differences in the direction, pattern and timing of resynchronisation. In some cases, the acrophase of the rhythm adapted almost completely within three days, whereas in others it failed to resynchronise within eight days. Adaptation of the circadian rhythm to the new time zone occurred by both a phase delay and a phase advance, and it is possible that small changes in the timing of rest periods and the exposure to light during and immediately after the flight may have been critical in determining the direction of adaptation. However, irrespective of the timing and direction of adjustment, the amplitude of the rhythm was reduced for at least three to four days after arrival.

As well as the disruption of the circadian rhythm, there were persistent changes in the structure of sleep and in performance and alertness. Total sleep times were reduced and sleep efficiency was poor on the second and third nights after the flight (the first night was not recorded), and even on the fourth night, three of the 12 subjects achieved less than five hours sleep. Changes in the structure of sleep were even more persistent: levels of REM sleep were low on the nights immediately after the flight, but by the sixth night they had increased to almost 40% of the total sleep time.

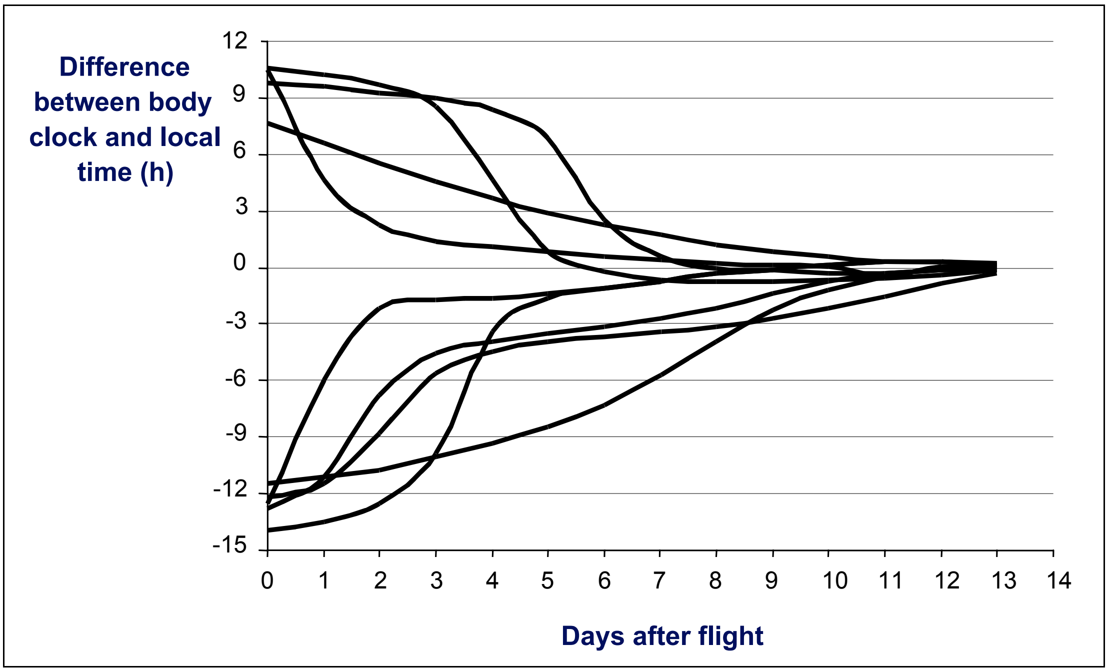


Figure 12 Acrophase of the Temperature Rhythm after a 10-hour Eastward Time zone Change

Difficulties in sustaining performance were observed for at least six days after the flight. There were very large decrements in the afternoon when, normally, an increasing circadian trend in alertness would ensure that performance could be maintained. This deterioration occurred independently of the direction of adaptation and, taken with the persistent effects on sleep, indicate the extent of the problems of adapting to very large time zone transitions.

4.4 Sleep Patterns: Long-haul Routes

To determine the impact of different duty schedules on the sleep patterns of aircrew, a sleep-log questionnaire was distributed to a random sample of approximately 25% of the aircrew on British Airways long-haul operations [23]. Information on the timing, duration and subjective quality of each sleep period was obtained from 241 aircrew, covering a total of 2,201 separate flying duty periods.

The majority of duty schedules consisted of a series of return trips, involving no more than three nights away from base, with the most frequent destinations in the north-east USA, followed by the west coast of America, south east/central America and the Far East. There were also some longer trips to Australia via the Far East and, in the period covered by the survey, some crews were also based in Australia.

The results revealed major differences in the sleep of the crews after westward and eastward flights. On westward trips, most aircrew slept slightly in advance of local time, especially on the first night. Some sleep problems persisted throughout the layover period on the west coast of America, but there was no strong evidence of difficulties coping with trips to the east coast, even when they involved layover periods close to 24 hours.

On long eastward trips, patterns of sleep were much less regular. Some aircrew attempted to sleep on local time, while many sleep periods were delayed closer to home time. There was some evidence to suggest that recovery after the outward flight was more easily achieved after a landing late in the day. In addition, early departures on the return leg caused severe problems with the truncation of sleep of the night before departure.

The greatest disruption of the sleep-wake pattern occurred on the Australian trip, with frequent napping as well as short, and sometimes exceptionally long, periods of sleep. It is likely that circadian rhythms were severely disrupted throughout the time spent in Australia, since the crews did not stay long enough for the rhythms to adapt to local time. On the majority of the trips involving time zone transitions of five hours or more, circadian rhythms did not appear to adapt to local time and, as a result, the recovery of sleep after the return home was complete by the third night. There was no evidence of a different pattern of recovery even after the longer Australian trip.

An important outcome of this study has been the establishment of an extensive database of information on the sleep patterns of aircrew on long-haul flights. This has proved invaluable in addressing many of the questions related to aircrew fatigue that have arisen in the intervening period.

4.5 Sleep Patterns: Short-haul Routes

This study was carried out to obtain an overall assessment of the impact on sleep patterns of the schedules operated by charter companies, and it was subsequently extended to cover air-freight operations [24]. The methodology involved sleep logs and was similar to that used for the long-haul study. A total of 175 logs were returned, from 14 of the 18 companies targeted, and the schedules they covered included 2,732 individual duty periods.

The majority of passenger operations involved daytime schedules with a large number of early starts (defined as starting earlier than 07:00) and some overnight flights. Most freight operations were overnight, with frequent periods of two or three consecutive nights.

When a duty period started before 09:00, the duration of the preceding sleep period was reduced, as the crews did not advance their bedtime sufficiently to compensate for the early start. The loss of sleep amounted to approximately 30 minutes for every hour that the duty period advanced between 09:00 and 05:00. During schedules involving consecutive early starts, the sleep deficit accumulated and levels of alertness on retiring to bed tended to deteriorate.

During schedules involving night duties, the duration of daytime sleep was over 2.5 hours less than normal, and crews frequently napped later in the day in preparation for the following duty period.

For the analysis of sleep duration and quality, the first use was made of statistical models (mixed mode, unbalanced ANOVA and regression models) which have since been used extensively for the analysis of aircrew alertness. These models are extremely effective in the estimation of the individual influence of a factor, when several significant factors are present, and they are most appropriate for the analysis of the unbalanced data that are collected in this type of study.

Using these techniques, it was possible to identify the individual influence of the factors that affected either the duration or the quality of sleep during these operations. These included:

a) the time of day;

b) the recent sleep history as measured by the S-process [see 3.2];

c) the duration of the rest period;

d) the time to the start of the next duty;

e) the previous rate of working;

f) the number (if any) of consecutive night duties; and

g) the nature of the next duty period (flying, standby, etc.).

The factor that had by far the greatest effect on the duration of sleep was the time of day. The mean duration of sleep starting between 21:00 and 01:00 was greater than seven hours. As the start of sleep was progressively delayed, its duration decreased to a value of 2.5 hours in the late afternoon. However, there was some evidence of a small secondary peak close to midday. Changes in the quality of sleep with time of day followed a similar pattern.

One important aspect of this study was the information it provided on the influence of rest period duration on sleep length. Compared with a rest period of over 14 hours, a rest period between 11 and 12 hours was associated with a loss of 40 minutes' sleep, one between 10 and 11 hours with the loss of an hour's sleep, and one under 10 hours with almost two hours' lost sleep.

5 Alertness Studies

5.1 Introduction

The previous sections have described studies completed with respect to the initial development of the SAFE prototype. They involved detailed physiological monitoring in both the laboratory and field, and many focused on the effects of irregular patterns of work on sleep and the circadian rhythm. The nature of these studies involving intensive monitoring of participants meant that it was only possible to cover a relatively small sample both of pilots and of different types of schedule. To validate the model with respect to a much wider range of operations, a methodology was developed to monitor aircrew alertness in-flight. It comprised three main components:

a) Diary of sleep and duty;

b) Activity monitoring via a small wrist worn monitor termed an 'Actiwatch'; and

c) Performance monitoring using small hand-held computers.

In general, the diaries covered the entire period of the schedule of interest. In addition, a couple of days prior to departure and on return to base, information relating to sleep was requested. During duty periods, crews were asked to provide details of their pattern of working, subjective ratings of fatigue (Samn-Perelli seven-point scale) and/or sleepiness (Karolinska Sleepiness Scale nine-point scale) and information relating to in-flight sleep (if appropriate). Throughout a schedule pilots reported details about their sleep. Details of the subjective scales are provided in Appendix B.

Small wrist-worn monitors called 'Actiwatches' were used to monitor activity. The information recorded enables the pattern of sleep and work to be determined and a check to be made with the data recorded in the diaries. Using these data it has also been possible to determine short periods of inactivity and hence brief episodes of sleep, for example on the flight deck. Depending on the nature of the study and the time available for testing, various performance tests have been presented on individual Psion computers, which the aircrew have carried with them on the flight deck.

A total of seven studies, including both long-haul and short-haul routes, have been carried out using this approach. These are described in the remainder of this section. However, the first validation was carried out using data provided by Dr Wegmann and Dr Samel of DLR, Cologne [25]. In a series of major studies in the early 1990s, they collected both physiological and subjective data from aircrew on unaugmented long-haul operations. These covered Atlantic crossings [25] and a north-south schedule [26], and are described below.

5.2 The Atlantic Crossing

The predictions of the model were compared with subjective data collected from 22 pilots during two return flights across the Atlantic [27]. The first trip (12 pilots) consisted of a return flight from Düsseldorf (DUS) to Atlanta (ATL) across six time zones. The outward (westward) flight was during the day, with an overnight return after a layover period that included three local nights. The second trip (10 pilots) was from Hamburg (HAM) to Los Angeles (LAX) across nine time zones. It also consisted of a daytime outward flight and an overnight return three days later (i.e. after three local nights).

The levels of alertness reported by the aircrew were reasonably close to the values predicted by the model. The best agreement was on the Los Angeles trip (Figure 13), where the model correctly identified the reduction in alertness on both the outward and the return legs, as well as the overall lower level on return. It also correctly forecast the much lower levels of alertness on the Atlanta trip on the return leg compared with the outward leg (Figure 14), but it did not predict the relatively small reduction with time into flight on both legs. However, the results from these initial comparisons were reasonably encouraging.

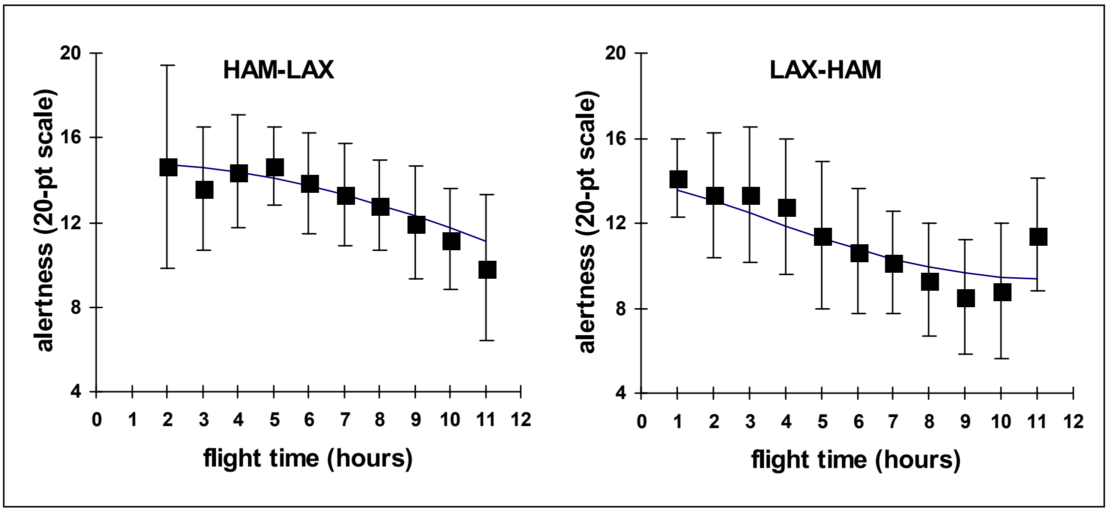


Figure 13 Observed (squares) and Predicted (continuous line) Alertness on the Los Angeles Trip

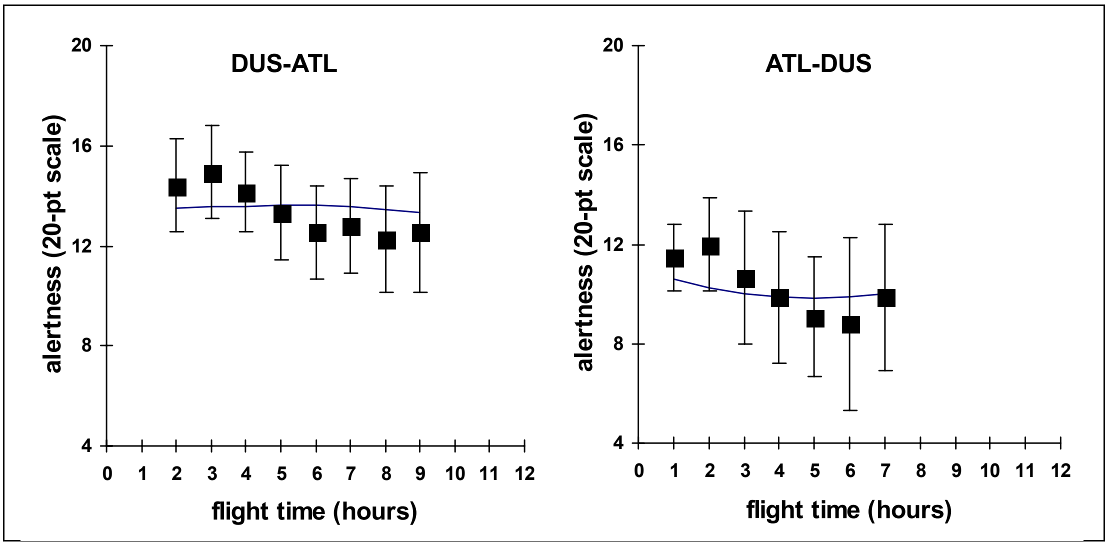


Figure 14 Observed (squares) and Predicted (continuous line) Alertness on the Atlanta Trip

5.3 The North-South Route

In this study, levels of alertness were obtained from 22 pilots on the return trip between Frankfurt (FRA) and the Seychelles (SEZ). The flights were on consecutive nights, separated by a rest period of approximately 12 hours. The outward flight departed from Frankfurt at 21:45 local time, and arrived at 09:10 local time in the Seychelles, which were two time zones in advance of Frankfurt [26].

As shown in Figure 15, agreement with the model was much poorer than on the Atlantic crossings. The model correctly predicted the strong downward trend on both legs, since both flights ended close to the circadian trough. However, levels of alertness were lower on the return than on the outward leg, whereas, according to the model, they should have been higher, since most aircrew were able to achieve a reasonable length sleep during the preceding rest period.

The reason for this disagreement was unclear. It seemed that the model was overestimating the recuperative value of daytime sleep on the short layover. This may have been a factor relating to daytime sleep per se, although laboratory studies have suggested that this is not the case. Alternatively, it may have been related to the sleeping environment in the hotel. The possibility that disturbances in the hotel associated with light and noise may lead to impaired daytime sleep and reduced levels of alertness on the following night, were investigated in later studies [see 7.4].

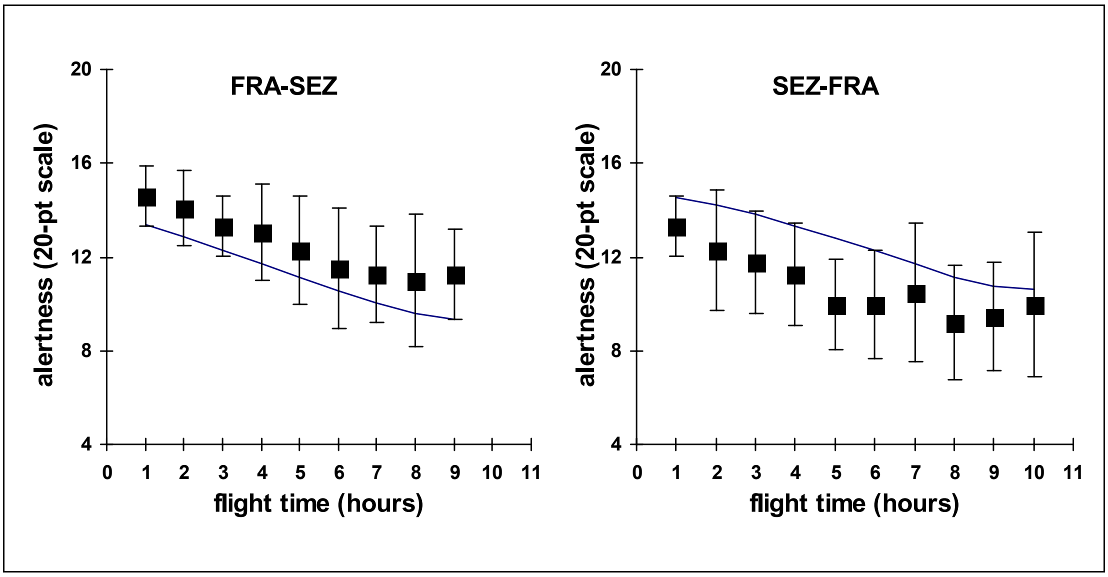


Figure 15 Observed (squares) and Predicted (continuous line) Alertness on the Seychelles Trip

5.4 London-Sydney Route

The first study to implement the methodology outlined in section 5.1 was an investigation of the London to Sydney route. At the time of the study, the London-Sydney route was the longest eastward time zone transition (11 hours in the northern winter) operated by British Airways crews and was reported to be the most disruptive. As described earlier (section 4.3), long eastward transitions have been associated with a marked deterioration in performance which can persist for at least six days. The failure of the model to predict the extent of this deterioration required further investigation and this study provided the opportunity to determine whether this disparity extended to aircrew. It also enabled the methodology for monitoring on the flight deck to be tested.

Two separate studies of the London-Sydney route were completed, one during March 1997 and the other in January 1998. A number of problems were encountered during the first study. The schedule of flights was disrupted, which meant that only a few of the individuals completed the schedule as originally planned. Therefore, the study was repeated in January 1998, when all crews followed the same duty pattern [28]. Data from this second study were used to validate the model.

The return trip to Australia was 10 days in duration and included six individual flights (Figure 16). Crews flew from London to Bangkok (flight duration 11:25 hours) where they had a 48-hour layover before departing for Sydney (flight duration 8:55 hours) where they had a layover of over 48 hours, which included a shuttle to Melbourne. Following the return flight to Bangkok, crews spent 48 hours in Thailand before returning to London.

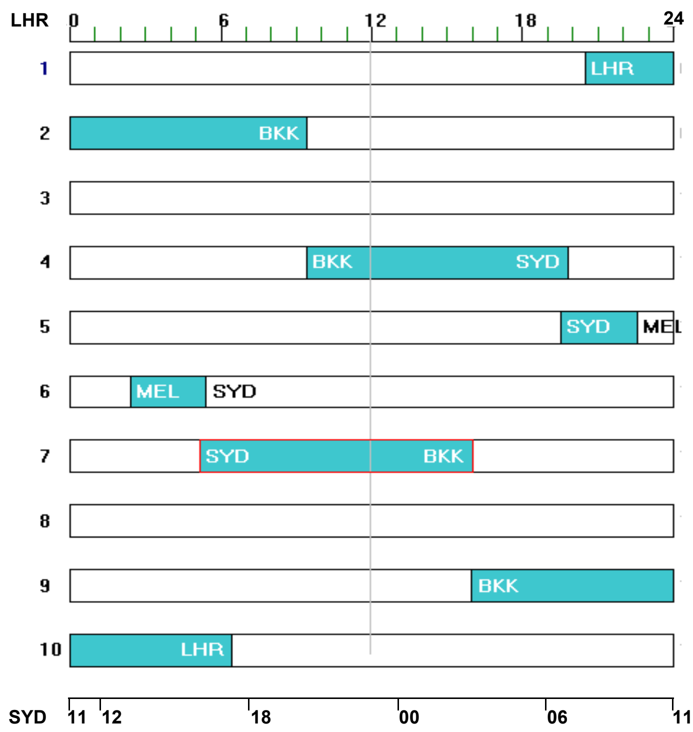


Figure 16 Schedule of Flights during the London-Sydney Route

Subjective levels of alertness varied between flights and with time into flight. The least fatiguing flight was the outward leg between Bangkok and Sydney, while the most fatiguing was the final leg between Bangkok and London. The increase in fatigue during the flights was most marked during the return phase, when the recuperative value of sleep in the bunk facilities was less than on the initial outward leg. Sleep was disrupted throughout the schedule, and levels of alertness on waking were particularly low after the first two sleep periods in Sydney.

The model was able to explain just over a quarter of the total within-subject variation in the subjective assessments of alertness. However, it did not predict the gradual increase in fatigue throughout the schedule. In addition, the model did not anticipate the high levels of fatigue at the end of the last three duty periods, and particularly at the end of the final leg. This accumulation of fatigue appeared to be associated with the continuous sleep disruption that persisted throughout the period away from base. Based on the findings from this study, a factor that related to the amount of cumulative fatigue associated with a schedule was included in the SAFE program. The study also established that the methodology employed was robust and acceptable to the aircrew. Using this methodology a series of validation studies were completed during the Haj between 1998 and 2000. The three studies are summarised below.

5.5 The Haj Studies

5.5.1 Background

The Haj (alternatively 'Hadj' or 'Hajj') is the fifth Pillar of Islam, which requires a pilgrimage to Mecca at least once in a lifetime for those who can afford it and whose health permits. It takes place each year and lasts for a period of five days, the exact timing of which is determined by the lunar calendar.

The transportation of pilgrims to Saudi Arabia from all parts of the world is a major undertaking involving many different airlines. Britannia Airways was involved in the air operation that carried pilgrims from Indonesia to Saudi Arabia and back again. The operation was completed in two phases. During phase I, the pilgrims were flown from Indonesia to Saudi Arabia and the aircraft returned to Indonesia empty of passengers. For phase II, the aircraft were flown empty from Indonesia to Saudi Arabia, and the pilgrims were flown back from Saudi Arabia to Indonesia. These two phases were approximately four weeks long and were separated by a period of 10 days. Britannia crews volunteered to participate in the operation and were based in Indonesia throughout.

Due to the distances involved and the type of aircraft employed, it was not possible to complete the passenger flights from Indonesia to Saudi Arabia in one single sector. Instead, when passengers were transported, the journey was completed as two flights (Figure 17). A short flight of around three hours between either Solo City (SOC) in Java or Ujung Pandang (UPG) in Sulawesi to Batam (BTH) off the coast of Singapore formed one sector, with a second sector, of around 10 hours, between Batam and Jeddah (JED).

Over a period of three consecutive years QinetiQ was involved, on behalf of the UK CAA, in monitoring the air operation and providing advice on ways to improve levels of alertness. During this period, the focus of the three studies altered with the evolution of the flying programme and as the factors contributing to fatigue changed.

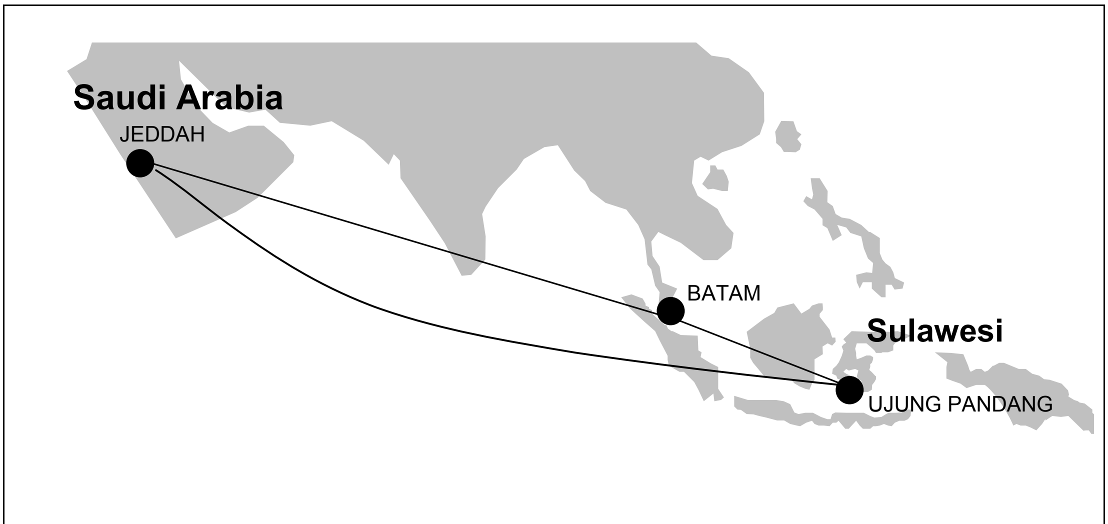


Figure 17 Pattern of Flying during the Haj Studies

5.5.2 **Haj 1998**

For this initial study Britannia Airways had applied to the CAA for a variation from CAP 371 in order to complete the flying programme. The variation allowed a two-pilot crew to operate the longer flight as a single sector. In granting the variation the CAA specified that the operation should be monitored to determine whether there were any problems with aircrew fatigue. In addition, the data collected could be used to validate the model further. Due to the timing of the flights, it also provided a unique opportunity to collect data from flights departing at two-hourly intervals throughout the day [29]. The majority of the flights carried a flight deck crew of three, but the crews did not rotate through the jump-seat.

Results from the study indicated that crews were struggling to stay awake during some of the flights. The most difficult times were towards the end of duty periods starting between 19:00 and 04:00 (LT) on the outward leg (Figure 18), and between 18:00 and 01:00 (LT) on the return leg. At other times of day the problems with fatigue were less severe. The indications were that duties starting between 06:00 and 15:00 (LT) on the outward leg, and between 04:00 and 11:00 (LT) on return, could be managed without the need for crew augmentation.

Crews generally slept well on the night before a flight, and they made considerable use of naps later in the day prior to an evening or an early morning departure. The main difficulty in Jeddah was obtaining sufficient sleep during a 30-hour layover that included only one local night. However, there was little evidence of problems with the hotel accommodation.

There were many instances of in-flight napping, particularly on the return leg, which helped to moderate the development of fatigue. However, the amount of sleep that the crews obtained in flight was insufficient to sustain levels of alertness at the most critical times of day. It was concluded that better quality rest would have been achieved if crews had been able to rotate through either the third seat or, preferably, through a bunk.

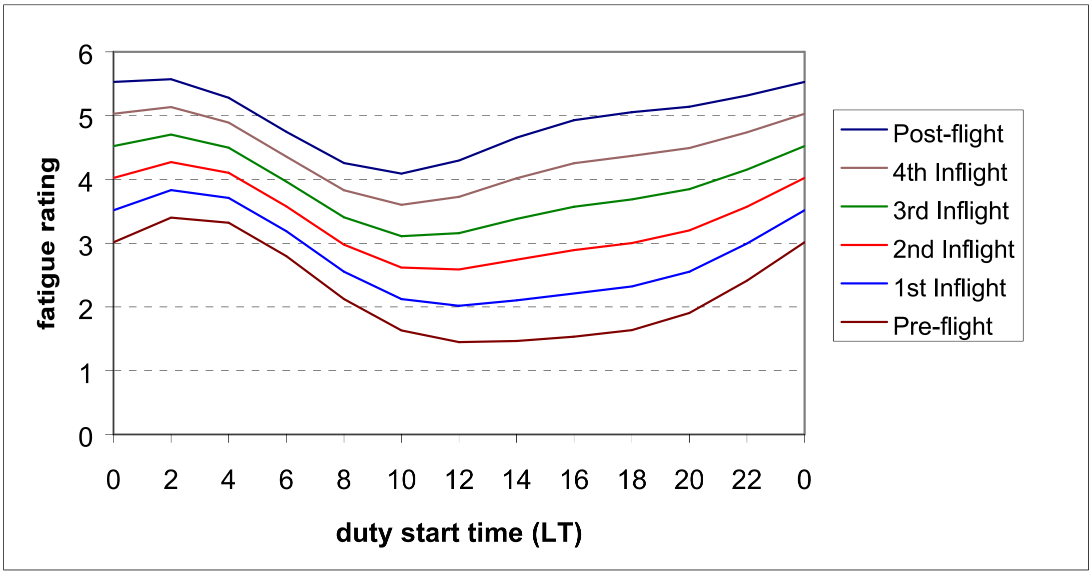


Figure 18 Trend in Subjective Fatigue during the Outward Leg of the Haj Operation

It was recommended that, for the following year, crew rotation should be implemented on the flights that departed at the most critical times of day, and that all three crew members should be able to operate in either the right or left-hand seat. In addition, bunks should be installed on some flights, and levels of alertness monitored to determine the benefit conferred by sleeping in a bunk.

Also, as a consequence of this study, more general recommendations were made for limitations to augmented flights overnight.

5.5.3 **Haj 1999**

During the following year the recommendations outlined above were implemented: crews rotated through the third seat and bunks were installed on all flights where passengers were not carried. The fatigue monitoring study was similar in design to the previous year, although the main focus of the analysis was on the value of in-flight rest taken either in the bunk or in the third seat on the flight deck [30]. There were also changes to the flying programme, which meant that the layover in Saudi Arabia was shorter than the previous year (between 27-28 hours).

The inclusion of a rest period during the flights was generally beneficial and the crews usually managed to achieve some sleep, even on those flights where a bunk was not provided. In spite of the provision of rest periods, there were occasions when crews were struggling to remain alert towards the end of some of the flights. This applied particularly to the second phase of the operation and to duty periods starting close to, and just before, midnight.

Sleep in the bunk was considerably better than in the seat, both in terms of the ability to fall asleep and the quality and quantity of the sleep achieved (Table 2). The rest provided by the bunk was sufficient to keep fatigue within acceptable bounds on all flights, with the possible exception of the very long flight on the second phase that started around midnight. However, the conditions for sleeping in both the seat and the bunk were not as good as they might have been. The seat was uncomfortable with poor leg support: the bunk was hard and the bedding inadequate. Nevertheless, there were clear indications that even sleeping in a seat provided considerable benefit by reducing the build up in fatigue towards the end of the duty period.

Table 2 Comparison between Sleep in a Seat on the Flight Deck and in a Bunk

	Seat	Bunk
Number succeeding in getting to sleep	65%	82%
Average sleep duration (hours)	0.57	1.22
Average sleep quality (scale 1 = extremely good 7 = extremely poor)	5.41	4.52

The shorter layover in Saudi Arabia was unfavourable with respect to sleep. Irrespective of the timing of the return flight, it did not give the crews the opportunity to sleep for at least part of two consecutive local nights.

For the following year it was recommended that the quality of the sleeping facilities should be improved. Ideally this would mean that bunks were provided on all flights. In addition, changes to flight time limitations in respect of layovers close to 24 hours were also recommended.

5.5.4 **Haj 2000**

Incorporating the recommendations from the Haj 1999 study, bunks were installed on all aircraft throughout the entire Haj operation in 2000, and steps were taken to improve the quality of bunk accommodation. The monitoring did not include diaries, but data were collected during each duty period using hand-held computers and

Actiwatches [31]. In addition, the opportunity was taken to compare the methodology for fatigue monitoring between that used by Air New Zealand and QinetiQ. The main difference between the two methodologies was in the performance task that was presented. Air New Zealand used a 10-minute choice reaction time task whereas QinetiQ used a shorter test of sustained attention.

The trends in the build up in fatigue during the long duty periods were similar to those seen in the previous Haj operations. However, mean levels of fatigue did not exceed critical levels at any time during the flight duty period and were lower than those of previous years. The improvements to the bunk and the installation of a bunk on all flights were beneficial and helped to ensure that fatigue was kept within acceptable levels during all flights.

Sleep in the bunk was better than that obtained in the previous year, with crews sleeping for longer and making fewer complaints of disturbed sleep. The average amount of sleep obtained varied between 30 minutes and almost two hours depending on the time of day and the time of the flight leg (Figure 19). Nevertheless, there were some indications that the sleeping facilities could be further improved.

The approaches adopted for fatigue monitoring by the UK and New Zealand groups were similar and comparisons between the two highlighted advantages and disadvantages with both systems. Overall, the two systems provided similar results.

Fatigue monitoring across the three successive operations enabled factors contributing to fatigue to be identified and, where possible, mitigated. The studies also provided a unique opportunity to collect data on the development of fatigue during duties starting at different times of day, the implications of altering the duration of a layover, and the cumulative effects of fatigue.

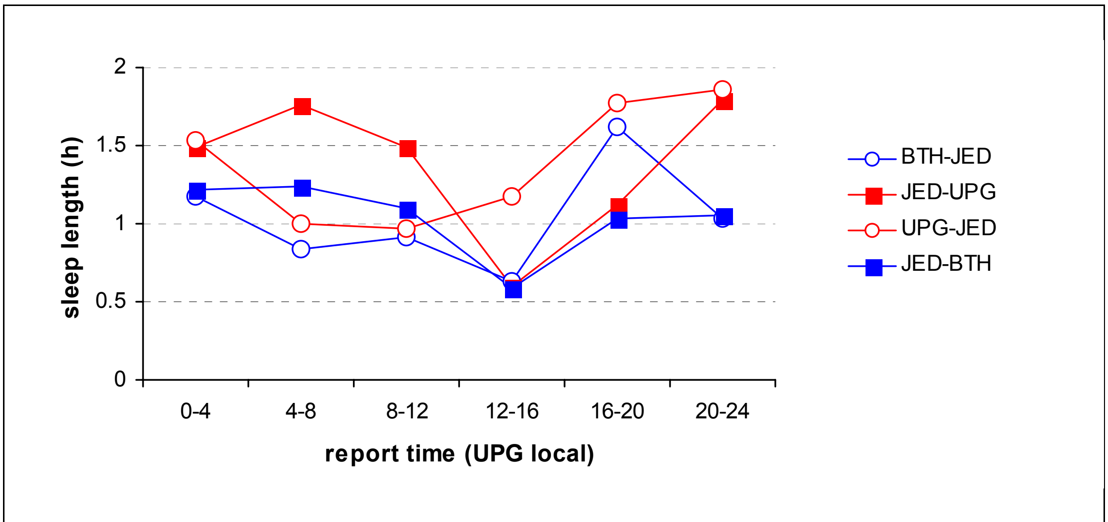


Figure 19 Sleep Duration during the Four Long Flights

5.6 Short-haul Studies

5.6.1 KLM UK

Previously the majority of data relating to aircrew fatigue had been collected on long-haul operations. Whereas it was recognised that crews involved in short-haul operations faced particular problems associated with high levels of workload, multiple sectors with short turn-round times, early starts and overnight duties, little data were available with which to validate the predictions of the model. To redress the balance, a study was undertaken with KLM UK to ensure that these factors could be represented in the model and, in particular, to investigate the fatigue implications of multiple sectors and early start times [32].

KLM UK operations involved multiple sectors, often with four flights per duty period and sometimes five or six. Crews operated from a number of bases in the UK as well as from the Netherlands, and most of the flights were of short duration either within the UK or between the UK and the north-western continental Europe. Early start times were commonplace, as were night stops. However, there were no scheduled operations overnight.

The diary study included estimates of fatigue at the end of each sector and estimates of the workload associated with each sector. Following discussions with some of the crews, it was decided to use the word 'hassle' to represent workload. This term was more likely to be readily understood by the crews, although it only encompassed one aspect of workload.

The data collected included a large number of early starts, with a third of all duties starting at 07:00 or earlier. Most involved two, three or four individual flights, with relatively few examples of a five or six-sector FDP. Sequences of duties on two, three, four or five consecutive days were common, and there were some schedules with duties on six consecutive days.

The duration and quality of the sleep period preceding duty improved as the start of duty became progressively later (Figure 20). The main change occurred before the early starts (report times before 09:00), when sleep was reduced by an average of 30 minutes for every advance of an hour in the report time. These early starts were associated with a large increase in fatigue that was equivalent, when the report time was earlier than 07:00, to the effect of increasing the length of duty by approximately three hours. Sleep improved slightly during a sequence of consecutive early starts, but there was no evidence of a corresponding improvement in alertness.

Other factors that interacted with early starts were the journey time to the airport, sleeping in a hotel instead of at home, and an advance of an hour in local time, associated with an overnight stop on the Continent. Although sleeping in a hotel reduced the journey time by an average of over 30 minutes, the quality of sleep was poorer and there was no improvement in alertness. The advance in local time was associated with a reduction in alertness on waking before an early report time.

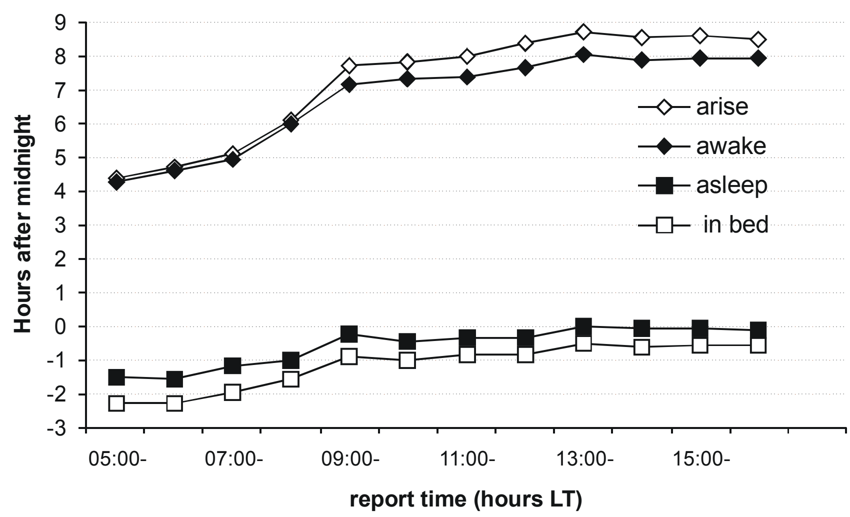


Figure 20 Timing of Sleep Prior to Duties Starting at Different Times of Day

From the analysis of levels of fatigue at the end of each flight, it was possible to determine the effect of each factor after correcting for the effect of every other significant factor. The effect of time of day was highly significant, and closely reproduced the trends observed under laboratory conditions, with lowest levels of fatigue in the late afternoon (Figure 21). The changes with time on duty were also highly significant (Figure 22). The pattern of increase could be explained by a linear function of time, with each hour of duty associated with an increase of 0.17 on the seven-point Samn-Perelli scale.

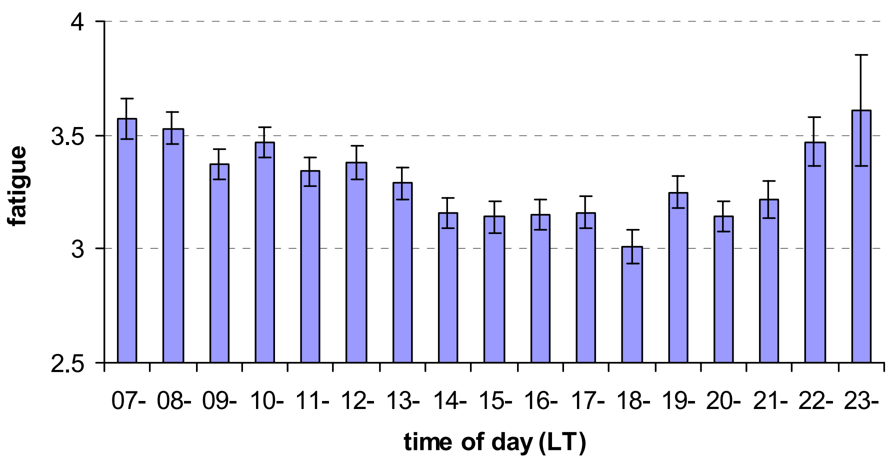


Figure 21 The Effect of Time of Day on Fatigue

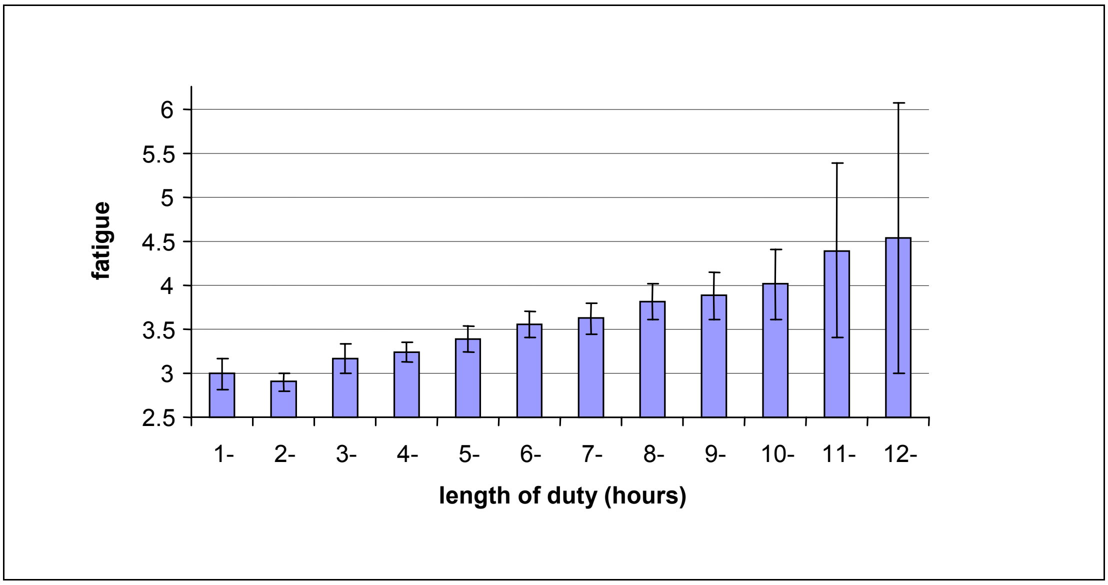


Figure 22 The Effect of Time on Duty on Fatigue

There was no difference with respect to fatigue between one and two-sector FDPs. However, when the number of flights exceeded two, each additional sector was associated with an increase in fatigue similar to that produced by an additional one hour 20 minutes of duty. Duties on consecutive days were associated with an increase in fatigue roughly equivalent to 20 minutes extra duty per day. The strongest influence on levels of fatigue at the end of a flight was the level of hassle associated with that flight. The amount of hassle increased significantly on flights into and out of Schiphol airport. It was also associated with duty periods that were unusually long, given the number of flights, possibly as a result of flight delays.

Based on the results from this study, it was recommended that two aspects of the FTL regulations relating to the definition of early starts were modified. In particular, it was considered that the definition of early starts should not allow an extra hour for sleeping in a hotel close to the airport and that the definition should be changed from local time to home time on the day after a one-hour time zone advance.

This study enabled the computer model to be adapted for short-haul operations, by incorporating the effect of multiple sectors and early starts. However, further information was sought on operations with three or more consecutive early starts, to confirm the trends suggested by these results.

5.6.2 Bmi Study: Short-haul Operations and the Impact of Early Starts

Bmi crews were asked to participate because at the time of the study bmi operated predominantly short-haul routes between the UK and mainland Europe, with a large proportion of early starts.

In general, the findings from the study with bmi confirmed those previously obtained from KLM UK [33]. The flying duties were broadly similar although bmi operated a larger number of very early starts (before 06:00), there were slightly longer sequences of consecutive early starts and the duty periods were on average longer.

As in the previous study, the main factor influencing fatigue in multi-sector operations was hassle. Other factors of almost equal importance were time of day, duty length and the number of sectors.

The effect of early starts appeared to be less severe than previously estimated. However, it became more pronounced when several early starts were operated without an intervening rest day. There was a cumulative effect associated with early starts. Each successive day was associated with an increase in fatigue, which was equivalent to an extra 40 minutes of duty per day. Fatigue also increased with the number of sectors flown (Figure 23). The increase from one to four sectors was equivalent to an additional 2.77 hours on duty.

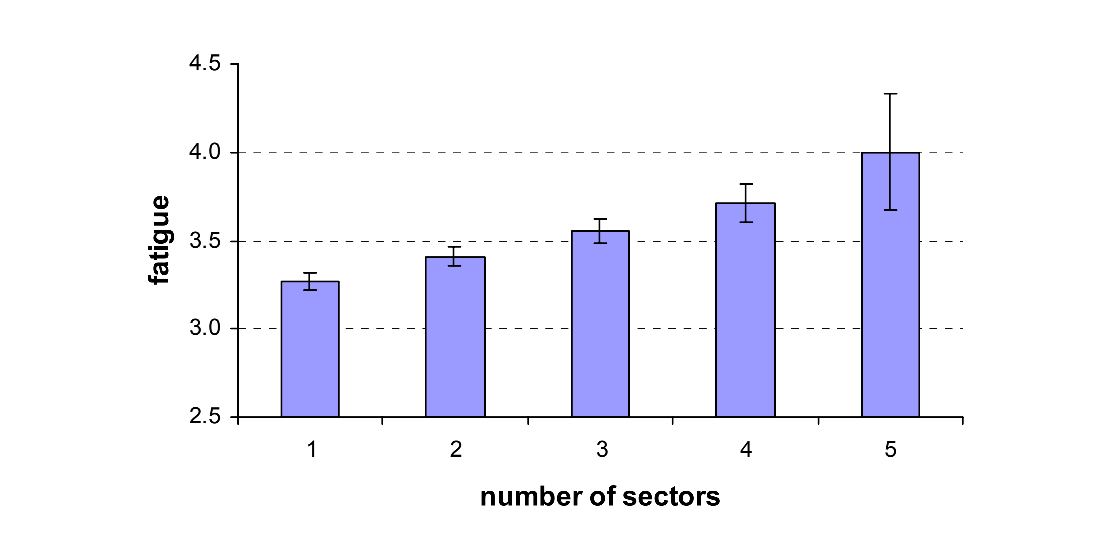


Figure 23 The Effect of the Number Sectors on Fatigue

The combined information from the KLM UK and bmi studies was incorporated into the model. However, there was still one aspect of short-haul operations which was not covered adequately in these first two studies, and that was the effect of night duties, and particularly consecutive night duties.

5.6.3 Night Operations – Britannia Airways

Previous data collected by DLR investigating return flights between Germany and the Seychelles [26] had indicated that the model might be underestimating the impact of consecutive night duties. Whilst the DLR study had provided an indication of the possible weaknesses in the model, it had only involved two consecutive night duties. It was unclear whether the problems associated with consecutive night duties become more severe as the number of duties increases. To address this issue, Britannia Airways, who were known to be undertaking a large number of night flights, were approached to participate in a study specifically targeting consecutive night duties.

Data from the diary study were collected from a mix of both long and short-haul duties although the analysis of night duties was confined to the short-haul destinations into Europe [34]. There was clear evidence of a reduction in sleep following duties that end progressively later in the night. For example, as the duty end time progressed beyond midnight, sleep time gradually reduced so that for duties ending between 00:00 and 02:00, the average sleep obtained was 6.4 hours. This reduced to 5.3 hours for duties ending between 03:00 and 05:00 and to 4.4 hours between 06:00 and 08:00 (Figure 24).

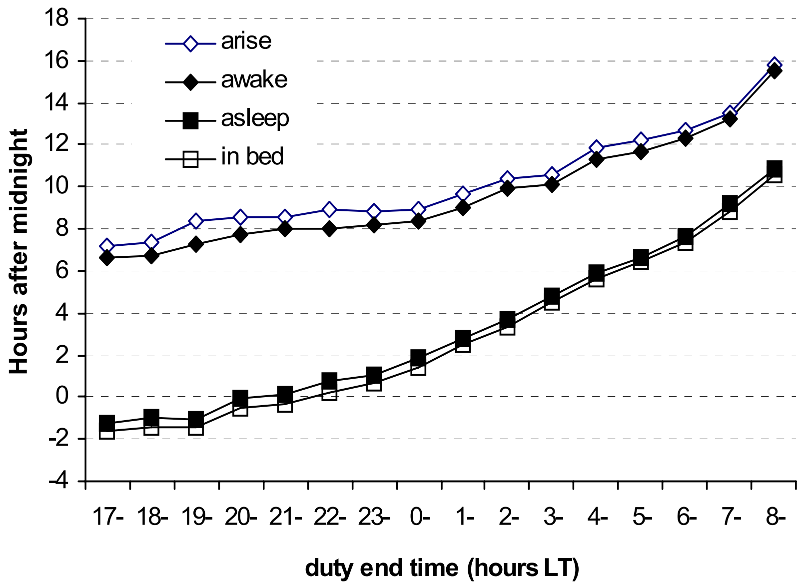


Figure 24 The Timing of Sleep Prior to Duty Starting at Different Times of the Day

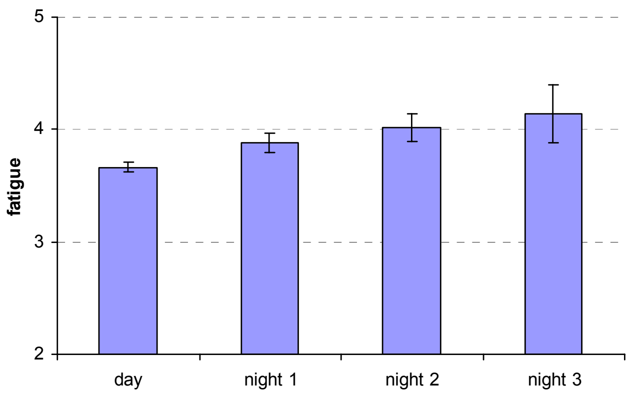


Figure 25 The Effect of Consecutive Late Finishes on Fatigue

As in the previous study, factors that influenced levels of fatigue were the time of day, the length of the duty period, and the number of sectors. In addition, the number of consecutive duties and the number of consecutive late finishes (Figure 25) also affected levels of fatigue.

The main objective of this study was to investigate the effect on aircrew fatigue of several consecutive night duties. However, as a result of the combination of two factors, this objective was not fully achieved. The first factor was the unfortunate timing of the study, which started in September 2001. It is most likely that the events of that month contributed greatly to the very disappointing participation rate, which was considerably lower than in previous studies (20% compared with between 30% and 50%).

The second factor was the relatively small number of schedules with three consecutive night duties. Combined with the poor rate of return, this meant that it was not possible to establish any significant changes over consecutive nights. Average levels over successive nights suggested that there may indeed have been a deterioration, but the numbers were not large enough to demonstrate an effect.

SAFE includes a factor associated with duties on consecutive days and, since this factor is independent of the time of day, it applies equally to night duties. There was insufficient evidence from this study to support any modification to this factor. However, the concern remained that the effect of consecutive nights was not being adequately represented. It was suggested that it might be necessary to consider whether further information could be collected on other night operations that would supplement the information collected here.

While the main purpose of the study was to investigate night operations, the results also provided useful comparisons with the results of previous studies. For example, the trend in fatigue as a function of time of day was remarkably similar to that reported in the bmi study, in spite of the different distribution of duties over the 24-hour clock. The highest and lowest levels of fatigue occurred at 05:00 and 18:00 respectively in both operations. The agreement with the bmi study also extended to the time-into-duty effect, and it is encouraging that both the effects are similar on different types of operation.

The increase in fatigue associated with the second sector was greater than in the bmi operations and contrasts with the results of the KLM UK study where there was no difference between the first two sectors. This probably reflects an essential difference between the two types of operation. The Britannia flights tended to be longer and duty periods generally consisted of only one or two flights, whereas many of the FDPs operated by bmi and KLM included three or four individual sectors.

The main difference between this study and the two previous ones was the failure to detect an effect associated with early starts. It could be argued that early starts represented a smaller percentage of the Britannia flights, and it may be that the aircrew gave far greater prominence to the problems associated with night flights. Nevertheless, the lack of an effect is surprising, considering the truncation of sleep prior to early start times that followed a similar pattern to those in the earlier studies.

Further data were required to validate the model with respect to consecutive night operations and, as suggested earlier, it was necessary to look to another type of operation, namely cargo operations, to obtain such data. This was achieved by carrying out a study with DHL, the details of which are described in section 7.3.

6 On-going Validation

6.1 General Comments

The model underlying the SAFE program is constantly being reviewed and, where necessary, modified in order to incorporate the most up to date information. Such information may be derived from studies published in the open literature, although there have been few studies of aircrew published recently. More frequently, information has come to QinetiQ directly, either from studies carried out for other organsations, or as the result of data-exchange agreements.

Recent work has involved several non-UK airlines. The data collected by these airlines have contributed significantly to the on-going validation of the model, and a brief description of some of this work is given in the following paragraphs. The value of these studies is that they have enabled the alertness model to be tested against a wider range of operations than those involving UK airlines only.

6.2 The Dubai-Perth Route

The main purpose of this study [35] was to provide information to validate the SAFE program in areas where the current version was possibly deficient. The flights studied were those operated by Emirates Airlines between Dubai and Perth. These were of particular interest for two main reasons: The outward flight departed at about 03:00 local time, and the on-board rest was taken in a seat rather than a bunk. The study also enabled the effect of duration of layover to be investigated, as crews were in Perth for either one or two days. The two schedule patterns are shown in Figure 26.

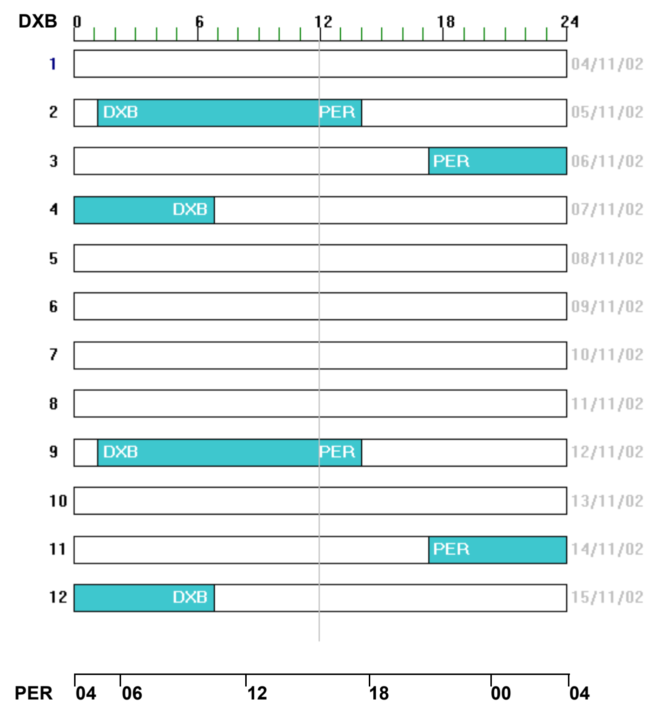
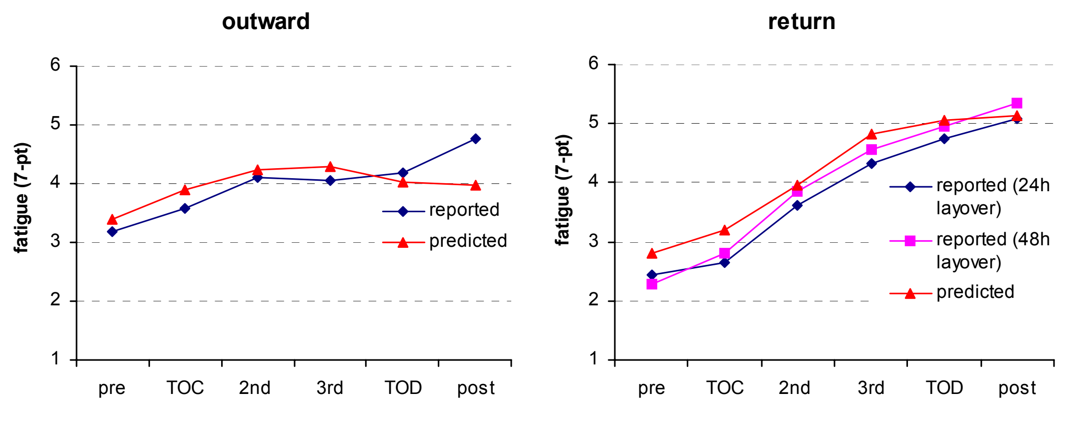


Figure 26 The Dubai-Perth Schedule for One- and Two-day Layovers

Diaries were completed and returned by 65 pilots, of whom 46 had a two-day layover in Perth. It was not expected that on flights as short as these (approximately 10.5 hours outward and 11.5 hours on return), crews would have taken two separate rest periods, but there were 34 occasions when two rest periods were taken. In general, two rest periods were not more efficient, in terms of the amount of sleep obtained, than a single one. Indeed, based on the level of alertness at the top of descent, some strategies for double rest periods were found to be inferior.

In general there was good agreement between the alertness levels predicted by the model and those reported by the crews during the flights (Figure 27). Levels of fatigue were higher at the end of the return flight, reaching almost five on the seven-point Samn-Perelli scale and approximately 6.5 on the nine-point Karolinska Sleepiness Scale at the top of descent (TOD). Also, as predicted by the model, there was no effect of layover duration on either assessment. These results therefore gave considerable encouragement that the model was capable of being applied over a wider range of operations.



TOC=top of climb; TOD=top of descent

Figure 27 In Flight Alertness (Dubai-Perth-Dubai): Comparison with Model Predictions

6.3 The Sydney-Los Angeles-Auckland Route

As part of an on-going programme of aircrew fatigue monitoring, Air New Zealand has been collecting information on the alertness levels of its crews on a wide range of different duty schedules. Under a teaming agreement between QinetiQ, Air New Zealand and the UK Civil Aviation Authority, a large quantity of the data collected have been made available to QinetiQ for the further development of the model. It is anticipated that this arrangement will enable several outstanding issues to be addressed, particularly those associated with long tours of duty and multiple time zone transitions.

The Sydney-Los Angeles-Auckland schedule consisted of a daytime flight from Sydney, landing in the early hours of the morning Los Angeles time, followed by an overnight return after a layover of either one or two nights in Los Angeles. The outward flight carried a double crew, while the return was three-crew. Figure 28 shows the predictions of the model compared with the levels of alertness reported by the crews at four different times during the flights. Again, the agreement was encouraging. The model also correctly forecast that there would be little change in levels of alertness if the crews spent a second night in Los Angeles.

Other schedules are currently being studied, including the return from Los Angeles with a double crew. The model correctly forecast that, as might be expected, alertness levels were higher with a double crew, although it slightly underestimated the extent of the improvement.

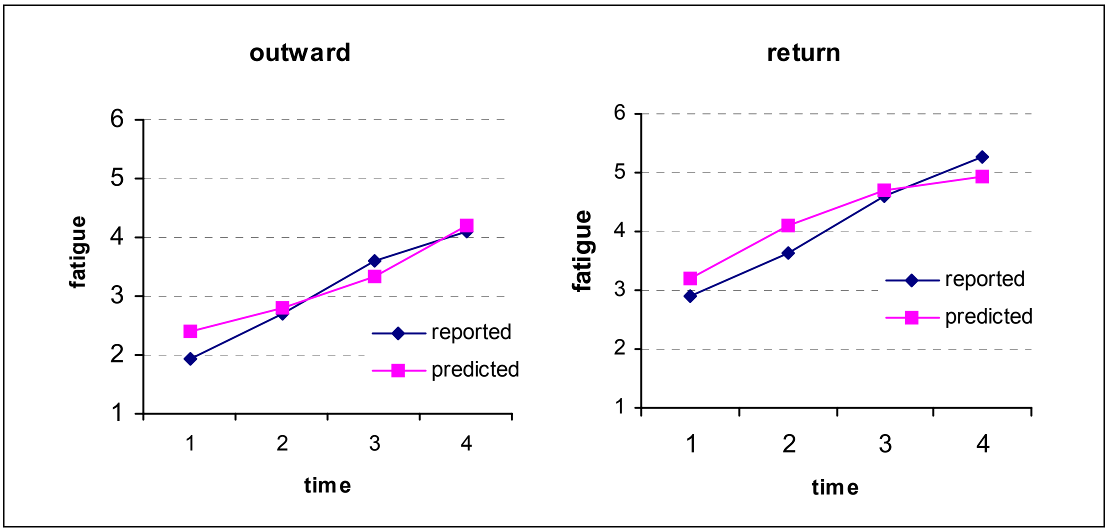


Figure 28 In Flight Alertness (Sydney-Los Angeles-Auckland): Comparison with Model Predictions

6.4 Eastward and Westward Flights to and from Singapore

As part of a European Consortium, QinetiQ has carried out studies for the Civil Aviation Authority Singapore (CAAS) in support of the introduction of the new generation of ultra-long-range (ULR) aircraft. In the absence of data from such operations, predictions of levels of fatigue and recommendations for crew augmentation were based mainly on the QinetiQ Alertness Model. The conclusion was reached that the proposed schedules could be safely operated by a crew of four, as long as the crews were able to divide their rest time into two separate periods.

Prior to the start of the ULR operations themselves, the opportunity was taken to validate the model against alertness levels on schedules that most closely resembled those that were planned. Accordingly, studies were carried out on the Singapore-London route and two routes between Singapore and the West Coast of America, with a stopover in either Hong Kong or Taipei [36].

Both routes involved a 24-hour layover at the final destination after a time zone transition of eight hours in either a westward or an eastward direction. The study therefore provided the opportunity to compare directly the effects on patterns of sleep of these long transitions, and to confirm the results of the much earlier international collaborative study. Whereas the earlier study was restricted to a relatively small number of pilots (only 12 on the London-San Francisco route), this study benefited from the participation of over 250 aircrew.

The patterns of sleep on layover after westward and eastward flights are shown in Figure 29. In this figure, the times refer to local time at base and the plotted lines are the proportion of aircrew sleeping at that particular time. After a westward flight, the majority of the crews adapted the timing of their sleep to the new time zone, although some chose to sleep a few hours earlier. From the earlier studies, it is likely that the quality of sleep was very good in the first part of the night, but subject to disturbance towards the end. Very few pilots slept in the afternoon or early evening.

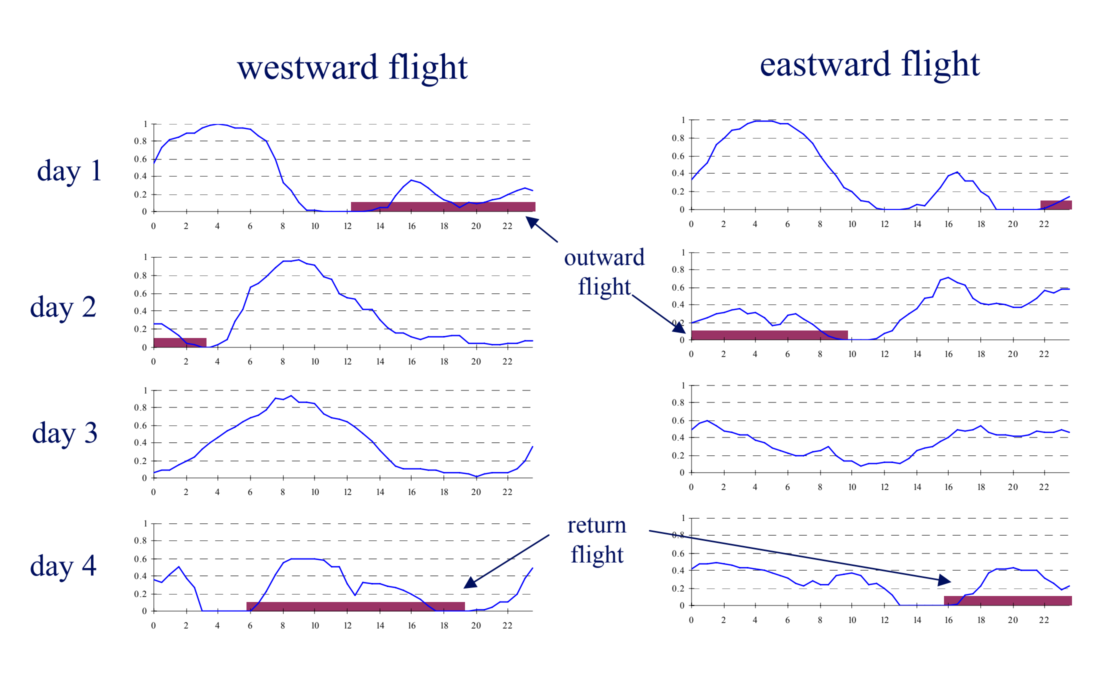


Figure 29 Sleep on Layover after Westward and Eastward Flights

The pattern after an eastward flight was different. There was scarcely any time during the two days when more than half the crews were asleep. Some attempted to sleep on local time, while others tried to stay on home time and, in the majority of cases, the pattern of sleep was variable with as many as five individual sleep periods over the two days.

The comparison of the levels of alertness reported on the Samn-Perelli seven-point scale with the predicted values is shown in Figure 30. The r^2 correlation coefficient for this comparison was 0.5 and the model correctly identified the most important trends, including levels of alertness at the top of descent. Where there were discrepancies, these tended to occur at the end of a rest period and to be associated with the prediction of the size of the effect of sleep inertia. The variability of the sleep inertia effect is well known, as well as the rapid change in alertness in the few minutes after waking. This is always likely to be an area of uncertainty for the model predictions.

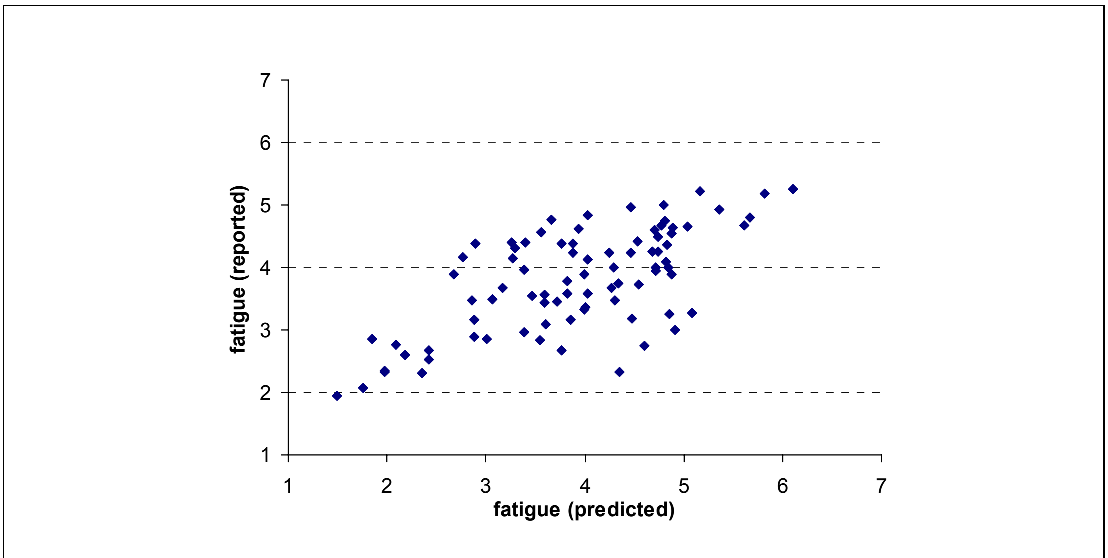


Figure 30 Reported and Predicted Fatigue on the Singapore Routes

Further studies are currently under way on the ultra-long-haul operations themselves, and these will provide valuable additional information, in particular about the effect of different in-flight sleep strategies.

7 Main Areas of Uncertainty

7.1 Background

The various validation studies that have been carried out have enabled the model to be improved considerably, and it can now provide a realistic assessment of fatigue levels associated with a large number of different types of operation. However, there are still some issues that need to be addressed. There are also some types of operation that it has not been possible to validate at this stage, particularly those that involve an interaction between different factors. This applies, for example, to short-haul schedules with an adverse juxtaposition of early starts and late finishes and to long-haul schedules with different combinations of start times and duration of layover, particularly after a long eastward transition, from those already studied. The importance of cumulative fatigue, especially as the result of a succession of long time zone changes is another area where further information is required.

In this section, two issues are covered where, although some uncertainty still exists, it has recently been possible to make some progress. One of these relates to sleep inertia, and the reduction in alertness that aircrew may experience in the period immediately after awakening from a sleep or nap taken either in a seat on the flight deck, a cabin seat or in the bunk facility provided on the aircraft. A study carried out to investigate this effect is described in Section 7.5.

The other issue addressed here is night operations and, in particular, the possible cumulative effect of duties over several consecutive nights. The issues raised by the Seychelles study [26], where low levels of alertness were observed on the second night, have already been described (Section 5.3). These were not adequately resolved by the Britannia study [34], due to the disappointing number of returns from consecutive night operations. However, it has been possible to make some progress. The possibility that daytime sleep in a hotel prior to a night-time flight may not be as recuperative as previously thought has been investigated in the laboratory (Section 7.4). In addition, the effective of consecutive nights in two different types of air operation has been studied, those of police helicopters (Section 7.2) and air freight (Section 7.3).

7.2 Police Helicopter Operations

The principal objective of this study was to investigate the fatigue implications of schedules involving different sequences of consecutive nights. The crews were operating a sequence of duties of either 2/2 (two days, two nights, four days off) or 5/5 (five days, five off, five nights, five off).

Due to the nature of the operations it was not possible to complete in-flight testing; instead the performance assessment was completed at intervals throughout each duty period at the four Air Support Units (ASUs) that participated. Data relating to sleep were collected using diaries and Actiwatches. Flights were intermittent during the duty periods and crews were able to nap between flights at the ASU.

Whilst it was clear that performance and alertness deteriorated across the course of the night, this occurred irrespective of the sequence of the night shift and there was no evidence of a cumulative effect of fatigue as the number of nights increased (Figure 31). Equally there were no differences between the two shift patterns. It is probable that the low workload, intermittent periods of flying and the opportunity to nap during the night shift all contributed to the crews ability to cope with consecutive night shifts. However, whereas most crews were able to cope with five consecutive nights there was evidence that one individual was experiencing problems with the shift pattern [37].

Based on previous studies of shift work, the 2/2 system was the preferred shift pattern for this type of operation. At the time of the study, there was no evidence of any particular problems for those crews operating the 5/5 system and no reason to withdraw the system. It was recommended that new recruits should be monitored to ensure that they are able to cope with five consecutive night duties.

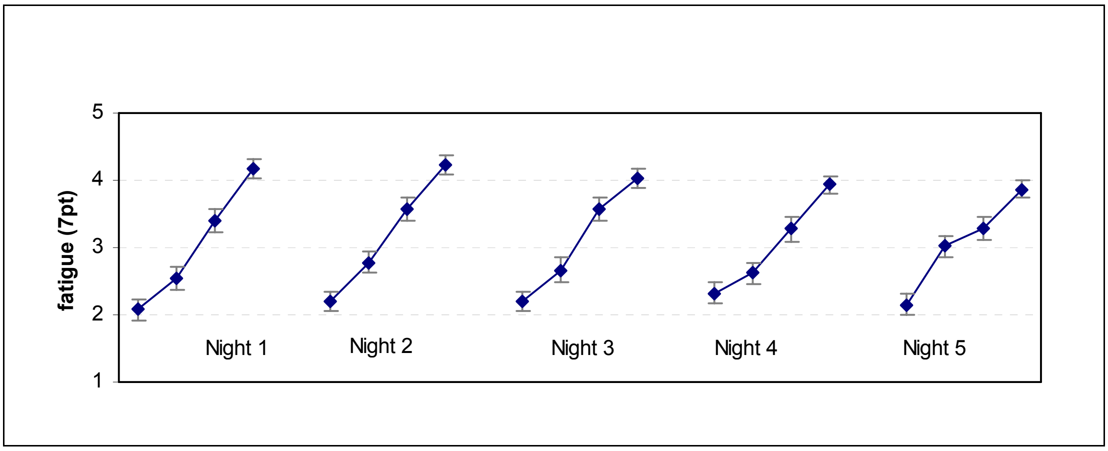


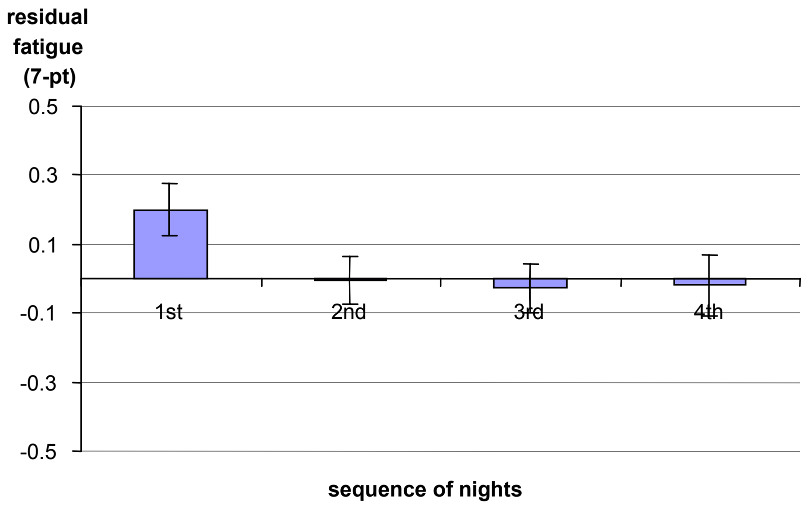
Figure 31 Fatigue during Five Consecutive Night Duties

7.3 Cargo Operations and Consecutive Night Duties

More recently, the requirement for further data relating to consecutive night duties was highlighted (see sections 5.6.2 and 5.6.3). Cargo operations were identified as a likely source of suitable data. Accordingly, DHL were approached, and agreed to participate in a study. At the time DHL were operating up to four, and occasionally five, consecutive nights, as well as schedules that incorporated 'split nights'. Split nights were operated instead of the longer overnight duty periods, and incorporated a 24-hour layover, away from base, which split the duty in two shorter duty periods, one in the evening and one in the early morning. This study provided the opportunity to investigate the effects on alertness of these split nights, in addition to the effects of consecutive nights [38].

There was no evidence in these operations of an increase in fatigue over four consecutive nights. This may be partly explained by the different nature of cargo, compared with passenger operations, and by an element of self-selection by the crews undertaking this type of work. Based on these results, no further changes were made to the implementation of consecutive nights in the SAFE program.

Split night duties were effective in limiting the development of fatigue overnight, and had no adverse effect on subsequent duty periods. In spite of the high percentage of overnight work, average levels of fatigue in this study were well within the range of earlier studies of short-haul passenger operations.



Residual Fatigue: fatigue after correcting for all other significant factors e.g. time of day, time on task

Figure 32 Residual Fatigue on Consecutive Night Duties

7.4 Effect of Noise and Light on Daytime Sleep: Two Laboratory-based Studies

For many night workers, one of the main problems is obtaining sufficient sleep between shifts. Indeed, daytime sleep tends to be of shorter duration and of poorer quality than that obtained overnight. Concern also extends to the quality of sleep of aircrew on layover. Data from the DLR investigation of the Seychelles route [26], suggested that during the overnight return flight crew alertness was much lower than expected, given the length of their reported sleep. However, under laboratory conditions the recuperative value of daytime sleep, allowing for its shorter duration, is similar to that of overnight sleep. Two obvious sources of possible disturbance are light and noise. To establish if the reduced alertness of aircrew could be explained by disturbed sleep, two laboratory-based studies were completed looking at the effect of noise or light on daytime sleep [39]. It was anticipated that the studies would provide information on the most beneficial environment for sleeping and provide input to the program on daytime sleep.

Two separate experiments were carried out, one of which investigated the effect of light, the other the effect of noise. In both experiments, six healthy middle-aged men reported to the laboratory at 09:00 after a reduced night's sleep at home. They retired to bed at 10:00 and, if necessary, they were awoken at 14:00 (15:00 in the light experiment). At hourly intervals from 04:00 to 10:00 and from 15:00 to 18:00, they were asked to complete a 10-minute battery of performance tasks and subjective assessments.

In the first experiment, the subjects were exposed to different levels of light while they were attempting to sleep in the laboratory. The levels of light were chosen based on 300 lux, which is roughly equivalent to moderate interior lighting. The brightest condition was 2400 lux, which is approximately equivalent to interior light levels on a sunny day. The conditions investigated were dark, 300, 600, 1,200, and 2,400 lux.

Prior to the second experiment, a pilot study was used to identify the noise level most likely to cause sleep disturbance. Based on this study, sounds at approximately 55dB(A) were presented to subjects via loudspeakers whilst they were in bed. To put this in perspective, noise levels of 35 dB(A) are approximately equivalent to that heard in a library, 65dB(A) to office noise and 125dB(A) to a jet aircraft taking off.

Eight different noise stimuli were used and were randomly presented, with a maximum of eight events per hour and a maximum duration of 10 seconds/event. Each subject performed the trial on six occasions, corresponding to six different conditions. With the exception of a no-noise condition, the conditions varied according to the timing of the noise stimuli during the sleep period.

Overall, light had only a small effect on the quality of daytime sleep. The main disturbance occurred when sleeping in the brightest condition (2400lux). Slow wave sleep (SWS), was reduced over the first 100 minutes compared with sleeping in the dark (Figure 33), although this reduction did not persist over the whole sleep period. In addition, total sleep time was reduced during the second 100-minute period, and individuals reported that their sleep had been disturbed. Some changes were also seen at lower light levels: at 1,200 lux more awakenings occurred compared with sleeping in the dark, and at 600 lux there was a reduction in total sleep time during the second 100-minute period.

Comparisons with 2,400 lux condition where *p<0.05; **p<0.01

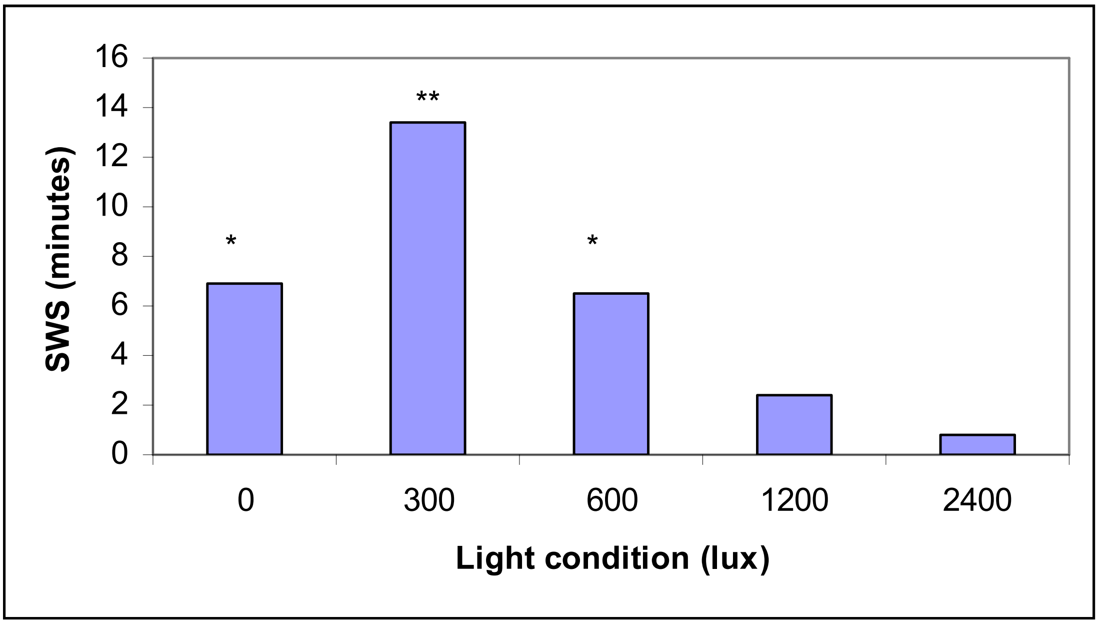


Figure 33 Changes in SWS with Light during the First 100 Minutes of Sleep

Noise commencing at or soon after falling asleep reduced the amount of SWS by approximately 50%. This reduction was associated both with the overall sleep period and with the first 100 minutes of sleep, which is roughly equivalent to the first sleep cycle. The time taken to enter SWS after sleep onset also increased when the noise began at lights out. There was no evidence that performance during the four hours after rising was affected by exposure to noise, and subjects did not report any differences in the quality of their sleep under the different noise conditions.

Since the principal effects of light were seen only in the brightest condition, it was concluded that light levels are unlikely to be a major cause of sleep disturbance in aircrew. Normal precautions, such as closing curtains and, in extreme cases, the use of eyeshades, should provide adequate protection.

Noise was found to be more likely to disturb sleep, especially when trying to sleep during the day. In the worst case, noise reduced the amount of SWS by 50%. Although no evidence of impaired performance was seen during the four hours after rising, this reduction in SWS may lead to impaired alertness towards the end of long duty periods. Indeed, this effect alone could account for the high levels of fatigue reported during the Seychelles study.

Overall, the main effect of noise was to reduce the amount of SWS during the first part of the sleep period, and it is during this time that the requirement and propensity for SWS will normally be highest. Thus, when the exposure to noise coincides with the early part of sleep, the individual may be unaware of any sleep disturbance. However, the structure of sleep may change and the overall level of sleep may be much lighter than in the absence of noise.

To avoid sleep disturbance, intermittent noise should be kept to a minimum. Necessary steps should be taken to ensure that such noises are kept to a minimum in hotel bedrooms when aircrew are attempting to sleep during the day. In situations where the only opportunity to sleep is afforded during the day, and noise is likely to disturb sleep, crews should consider the use of earplugs.

7.5 Napping and Sleep Inertia

Napping is a countermeasure to fatigue frequently used by aircrew and is implemented in a variety of situations e.g. prior to overnight duties, in-flight on the flight deck or in a bunk, and following overnight duties. A review of in-flight napping strategies [40] indicated that sleep inertia is the main factor limiting the effectiveness of naps. Sleep inertia is a transient period of impaired performance and alertness which occurs during the period after awakening, and which may severely limit the pilot's effectiveness and judgement if there is a requirement to perform any duties immediately after waking. However, information from the review highlighted that data were lacking on the duration and extent of any benefits conferred by a nap and of any performance impairments associated with sleep inertia.

To address these issues a laboratory-based study was completed to investigate the effectiveness of naps of different duration with respect to both their long-term benefits and the duration and magnitude of sleep inertia [41]. Many factors could influence the efficacy of a nap, including the time of day and whether the nap is taken in anticipation of increased sleepiness later in the flight or when severe sleepiness has already become established. In this study, the nap was scheduled between 01:45 and 03:00, corresponding to a time of increased sleepiness on the circadian clock. This represents a typical time on the circadian clock when a nap might be taken, for example on a return flight to the United Kingdom from the United States.

Twelve healthy male volunteers between the ages of 20 and 30 years each reported to the sleep laboratory on six separate nights. On one night they remained awake throughout, while on the other nights they were allowed to sleep for 10, 20, 30, 40 or 60 minutes, in each case waking up at approximately 03:00. The nap was monitored on-line from the time of sleep onset to ensure that the duration of sleep was as close as possible to the desired time. Performance was monitored immediately on waking and at regular intervals until 07:30.

On average, subjects reached stage 2 sleep, which corresponds to normal restful sleep, after 15 minutes. In all napping conditions, they achieved some SWS, which is thought to be associated with higher levels of sleep inertia. Amounts of SWS varied from less than a minute in a 10-minute nap to over 12 minutes in a 60-minute nap.

The effects of sleep inertia increased with the duration of the nap (Figure 34). Some effects were evident even after a 10-minute nap, but these were limited to the subjective assessments of fatigue and sleepiness. Performance decrements were only statistically significant after a nap of 30 minutes or longer. Two minutes after the end of a 60-minute nap, reaction times were increased by over 8% compared with the pre-nap value, a level which would not have been reached for another 2.5 hours in the no-nap condition.

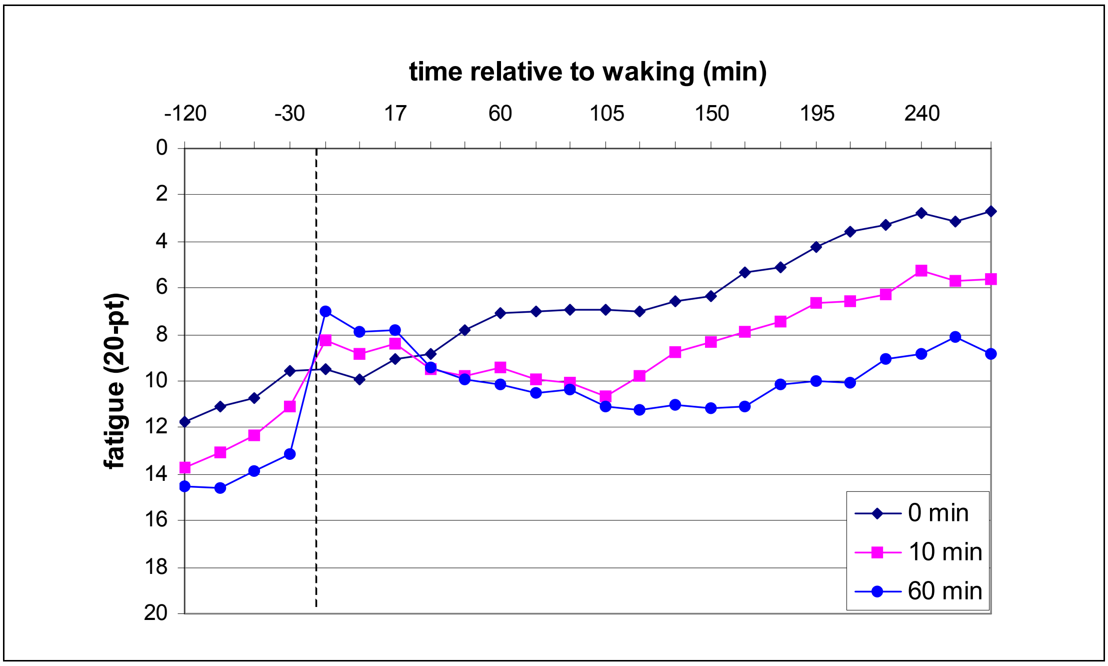


Figure 34 Subjective Assessment of Fatigue for the No-nap, 10 and 60-minute Naps (dotted line indicates the time of waking)

There were significant long-term improvements in both performance and the subjective assessments of fatigue and sleepiness after naps lasting for 40 or 60 minutes. The improvement in both performance and subjective levels of fatigue was greater, the longer the nap.

This study has implications for flight-deck napping and naps taken in a bunk. It appears that major long-term benefits from in-flight napping cannot be achieved without a significant amount of sleep inertia lasting for a period of about 30 minutes immediately after waking. It may be that the sleep inertia is a price that has to be paid for the benefits, in terms of improved levels of alertness, which may accrue later in the flight.

In these circumstances, a balance has to be struck between the long-term benefits and the risks associated with the removal of one of the pilots from active duty for a significant period of the flight. The greatest benefit in post-nap performance would be achieved if pilots could sleep for the majority of the flight, but this is clearly unrealistic.

For naps taken on the flight deck a reasonable compromise would be rest periods of 60 minutes, which would provide some benefit with respect to alertness. This would allow time for the individual to achieve 20 to 30 minutes of restful sleep, together with a period of 20 minutes after waking to return to full effectiveness.

The issue of any in-flight napping with a minimum crew raises questions about the acceptability of having only one pilot on effective duty for long periods during the flight, and the steps that would be required to ensure that that this pilot remains awake and alert.

In a separate series of studies, physiological and physical parameters were monitored in-flight to determine if it was possible to detect unobtrusively the occurrence of involuntary sleep on the flight deck [42][43]. The project involved two in-flight studies in which 24 British Airways aircrew participated. The outcome from this work was a recommendation for the development of an alertness alarm based on wrist inactivity.

Following the production of prototype device a study was completed in which each pilot wore an Actiwatch-Alert wrist-watch alarm (Cambridge Neurotechnology Ltd) during the entire cruise segment of the flight. The device was set to activate the alarm if no wrist activity was detected within a five-minute interval. Pilots were asked to carry out their normal practice with regard to cockpit napping. They completed a subjective evaluation of the alertness device concerning its acceptability, comfort and potential usefulness and were also asked to make other suggestions and observations.

The alertness device was effective at preventing unintentional sleep on the flight deck and was considered acceptable to most pilots [43]. During the overnight return flight there were a total of 15 alarm activations, of which only one was a false alarm (i.e. there was no evidence of reduced alertness or sleepiness in the objective measures). Nevertheless, a number of improvements to the device were identified, which included preventing accidental switching on/off, modifying the software to take account of brief episodes of movement during sleep, and providing a user input facility to allow the device to be used in conjunction with planned cockpit napping.

7.6 The London-Hong Kong-Sydney Route

Finally, a brief account is given of a study carried out with Virgin Atlantic Airways to investigate issues related to long eastward flights. Unfortunately, it proved difficult to recruit volunteers for this study, and the results are based on a relatively small sample.

The purpose of this study was to investigate the effect of schedules involving long eastward time zone transitions. It involved a schedule that had many similarities with one studied very early on in the validation process (see Section 5.4). However, this time it was hoped to collect data from a far larger sample to gain a better understanding of the complex issues associated with these potentially demanding schedules.

The schedule itself (Figure 35), involved a long (approximately 13-hour) eastward flight across seven tome zones between London and Hong Kong, followed by a shorter (approximately nine-hour) flight across two time zones between Hong Kong and Sydney. There was a two-day layover in Hong Kong, a layover of approximately 31 hours in Sydney, and another of two days on the return through Hong Kong. The London flights carried a double crew, whereas the Sydney flights carried a crew of three.

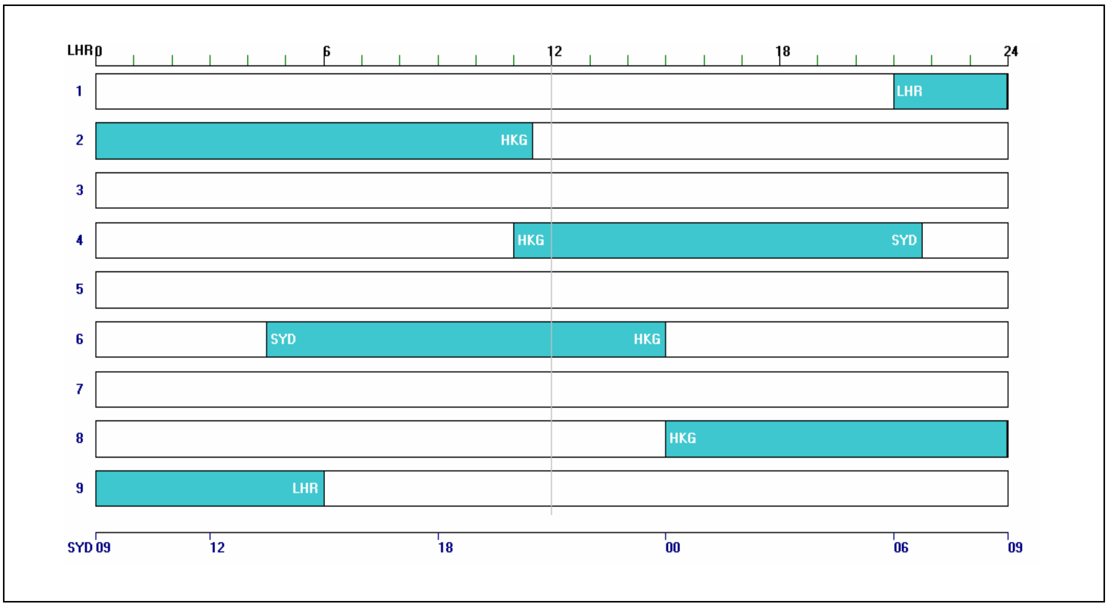


Figure 35 The London-Sydney Schedule

Despite intense efforts, only 23 pilots volunteered for this study, and the conclusions that could be drawn were therefore very limited. As predicted, the lowest levels of alertness tended to occur on the final flight. However, the relief crew were more fatigued on this flight, and the main crew less fatigued, than the SAFE predictions, although, being based on a small sample (only n=6 for the relief crew), these differences should be treated with some caution.

The pattern of sleep on layover was generally similar to the SAFE prediction, with the pilots sleeping for slightly longer than predicted in Hong Kong, and for slightly less long in Sydney. As previously observed (e.g. Section 6.4), sleep was fragmented with pilots taking between five and 12 (average eight) individual sleep periods during the three layover periods. Overall, including their reported in-flight sleep, they slept for an average of approximately 52 hours during a period of between seven and eight days.

In contrast to previous schedules studied, there was evidence that the crews took more than three days to recover after their return home. Trends in alertness prior to overnight sleep increased up to and including the fifth night ($p<0.01$), and the subjective requirement for more sleep on waking reduced continuously from the second to the fifth night ($p<0.05$) (Figure 36).

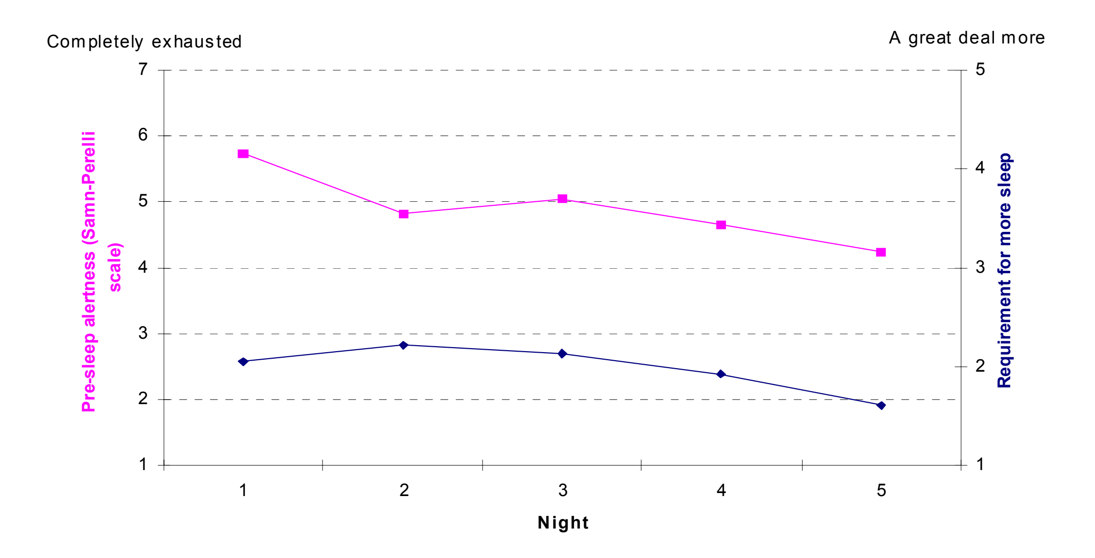


Figure 36 Recovery in Pre-sleep Alertness and the Requirement for Sleep Following the Return Flight to London

8 Current Position and the Way Forward

8.1 Development of SAFE

The proof-of-concept prototype, based principally on the QinetiQ Alertness Model, was produced early in 1997. Various improvements were made, mainly to the Graphical User Interface (GUI) before Version 1.2 was completed in December 1999. Among many other new features, this version incorporated a database of airport codes and information on time zones and daylight saving that enabled the user to obtain the correct local time at any location.

A beta version (Version 2.09) was released in May 2001, incorporating factors specifically related to the work of aircrew, derived mainly from the validation studies. In some cases, factors included in the original model were modified to reproduce trends observed in the aircrew data. These were:

a) the effect of early starts, derived from the KLM UK study (Section 5.6.1);

b) modified trends related to time of day, based mainly on the Haj 1998 results (Section 5.5.2);

c) the recuperative value of bunk sleep at different times of day, derived from a re-analysis of data from the bunk questionnaire study (Section 2.4.1);

d) differences between sleeping in a bunk and sleeping in a seat, from the Haj 1999 results (Section 5.5.3);

e) the effect of multiple sectors, from the KLM UK data (Section 5.6.1);

f) the reduction in the effectiveness of daytime compared with overnight sleep. This was based on the DLR data from the Seychelles route (Section 5.3) and the results from the laboratory experiments on the effects of light and noise on daytime sleep (Section 7.4);

g) the effect of working for several consecutive days, derived from the KLM UK study (Section 5.6.1). A rough estimate of the interaction of this effect with long time zone transition was based on the London-Sydney study (Section 5.4); and

h) a small effect due to time on task was included, influenced by the trends seen in the Haj 1998 and Haj 1999 studies (Sections 5.5.2 and 5.5.3).

The beta version also included an algorithm that predicted the timing of sleep (sleep generator). For short-haul routes, the main input to this came from the KLM UK study (Section 5.6.1). For the long-haul routes, the input was mainly from the sleep patterns in the BA long-haul study (Section 4.4).

Version 2.09 was widely distributed within the airline industry in the UK and, to a lesser extent, abroad. Based on the feedback received, Version 3.02 of the program was released in March 2003. This incorporated a large number of improvements both to the GUI and to the underlying model. The time-on-task effect was changed to represent a compromise between the results of the KLM UK (Section 5.6.1) and bmi (Section 5.6.2) studies. In addition, the results from the KLM study were used to establish the relationship between the Samn-Perelli and Karolinska scales and the output from the model.

8.2 The Use of SAFE

The most recent version of the SAFE program has been delivered to the CAA, and is currently being used as an additional aid in the evaluation of the fatigue implications of duty rosters. Essentially, it provides the CAA with an initial assessment, without the need to obtain expert advice in response to every single query. It can confirm those areas where there is unlikely to be a problem, and indicate those that may need further consideration for their fatigue implications.

Another area of application for the program, or rather for the model that underlies the program, is in the automatic generation of rosters. Present aircrew rostering programs do not incorporate fatigue issues implicitly. However, under their teaming agreement with the CAA and QinetiQ, Air New Zealand are currently incorporating the model into their rostering software. This will enable the generation of rosters that are optimised, not only with respect to cost, but also with respect to the alertness of the crews.

8.3 The Way Forward

Many advances have been made in our understanding of aircrew fatigue over the past few years, and the programme described in this report has made a major contribution, particularly through the development of the model. This was highlighted recently by the extent of the input made by the SAFE model to understanding the requirements for crew augmentation in the new ultra-long-range aircraft. Without access to the results of the modelling, the regulatory authority, in this case CAA (Singapore), would have had very little evidence on which to base any guidelines for these operations.

There are several issues, however, that will need to be addressed, before the model can be considered to be fully developed. Some of the areas of uncertainty have been discussed in the previous section, and it should be possible to make progress on many of these fairly rapidly. Others, like the issue of cumulative fatigue may prove to be more difficult, due to the problem of identifying current operations that could contribute useful data. Without these, the predictions of the model would be wide extrapolations, and it is likely that input from laboratory studies and from military operations will be required to provide rough estimates of the importance of this factor.

There are other areas where the model could be significantly improved. One of these is related to individual differences. The present model attempts to predict only average levels of fatigue whereas, in practice, pilots may respond quite differently to the same pattern of duty. This is particularly true, for example, after long eastward flight when both the circadian response (Section 4.3) and the pattern of sleep (Section 6.4) are extremely variable. Moreover, the concern that arises when mean levels of fatigue rise to a moderately high level (e.g. to level five on the Samn-Perelli scale), is not that the mean level itself is unacceptably high, but that the probability of an extremely high level in a subgroup of individuals is much increased.

Another area that could be addressed is the degree of detail that the program should include. At the moment, it is possible to change the pattern of sleep and, for example, to predict the benefit associated with taking a short nap in the few hours before reporting for duty. However, there is no provision to include the benefit of caffeine although pilots may often use caffeinated drinks, especially coffee, to sustain their alertness through a flight. There are many other factors that could be included, such as the quality of hotel accommodation, the distance of the hotel from the airport, commuting time, the hassle factor (one aspect of workload) associated with individual airports, the effect of standby, and so on. Information on many of these factors is already available or could be easily collected. However, it is not clear how useful it would be to extend the scope of the program in this way.

A final issue concerns the applicability of a model based mainly on subjective fatigue and simple performance tests that are unrepresentative of the task of piloting an aircraft. The critical factor for safety is not fatigue, or even sleepiness, but accident risk. As the accident rate for passenger aircraft is extremely low, in terms of distance travelled, compared with other forms of transport, there are few data on which to base a risk estimate. A recent FAA study has demonstrated a relationship between accident risk and distance travelled based on an analysis of 55 accidents over more than 20 years [44], and this may possibly provide a link to fatigue risk. Other information is available in the form of the pilot performance data that are currently being routinely collected by several airlines. While they are not necessarily related to accident risk, such data could provide a useful indication of the correlation between fatigue and performance that would help to underpin the model.

9 Glossary

Acrophase	The time during the day when the circadian rhythm reaches its peak value. For example, the acrophase of alertness normally occurs in the late afternoon.
Actigraph	A device used to record movement, typically worn on the wrist.
Circadian rhythm	An innate daily fluctuation of physiological or behavioural functions usually occurring with a period of approximately 24 hours.
Desynchronisation	When an individual's circadian rhythm is out of phase with the local environment. See synchronised.
Electroencephalogram	A recording of the electrical activity of the brain via (EEG) electrodes applied to the scalp. Together with recordings of the electro-oculogram (EOG) and electromyogram (EMG) it is used to classify the various stages of sleep.
Multiple sleep latency tests (MSLTs)	Used to provide an assessment of daytime sleepiness. Normally consists of a series of individual tests, spaced at 2-hourly intervals through the day. Individuals are given a 20-minute period in which to fall asleep. The time taken to fall asleep, i.e. latency is used to characterise sleepiness. Normal sleepiness is generally considered to be associated with latencies greater than 10 minutes.
Rapid Eye Movement (REM) sleep	Stage of sleep characterised by spontaneous rapid eye movements. Associated with dreaming.
Resynchronisation	Relates to circadian rhythms and the realignment following time zone transitions.
Sleep efficiency	The ratio of total sleep time to time spent in bed.
Slow Wave Sleep (SWS)	Sleep characterised by EEG waves of duration slower than 4Hz. Synonymous with stages 3 and 4 combined. Often referred to as 'deep sleep'.
Synchronised	Relates to circadian rhythms and is used to indicate when two or more rhythms are in phase i.e. have the same phase relationship, or when one rhythm is out of phase with the local environment.
Unacclimatised	Refers to an individual who is not adapted to the local time zone.

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Appendix A A Brief Note on Sleep

Sleep is a fundamental requirement for humans. The amount of sleep required for the maintenance of physiological and psychological health is around seven to eight hours per 24 hours, although this varies between individuals.

The electroencephalogram (EEG) is a measure of brain activity during sleep, variations in which enable sleep to be categorised into a number of stages. Stage 1 or 'drowsy' sleep usually occurs during the transition from waking to sleep. Stage 2 sleep normally occupies up to 50% of the sleep period. The time taken to reach the first episode of stage 2 is termed 'sleep onset latency', and includes any intervening stage 1 sleep. 'Deep' sleep (stages 3 and 4), otherwise known as slow wave sleep (SWS), predominates in the early part of the night and is influenced by the length of prior wakefulness. Episodes of rapid eye movement sleep (REM) occur at intervals, and are associated with dreaming.

A typical night's sleep pattern of a young adult is illustrated in Figure 35 below. Generally, the sequence of sleep stages during the night is: waking, stage 1, stage 2, stage 3, stage 4, stage 3 and then stage 2. At this point the first period of REM sleep occurs. It is followed by stages 2, 3, 4, 3 and 2 and a further REM episode. Sleep cycles recur throughout the night, with each cycle lasting around 90 minutes. As the night proceeds, the content of the sleep cycle alters, with less SWS and more REM sleep in the later cycles.

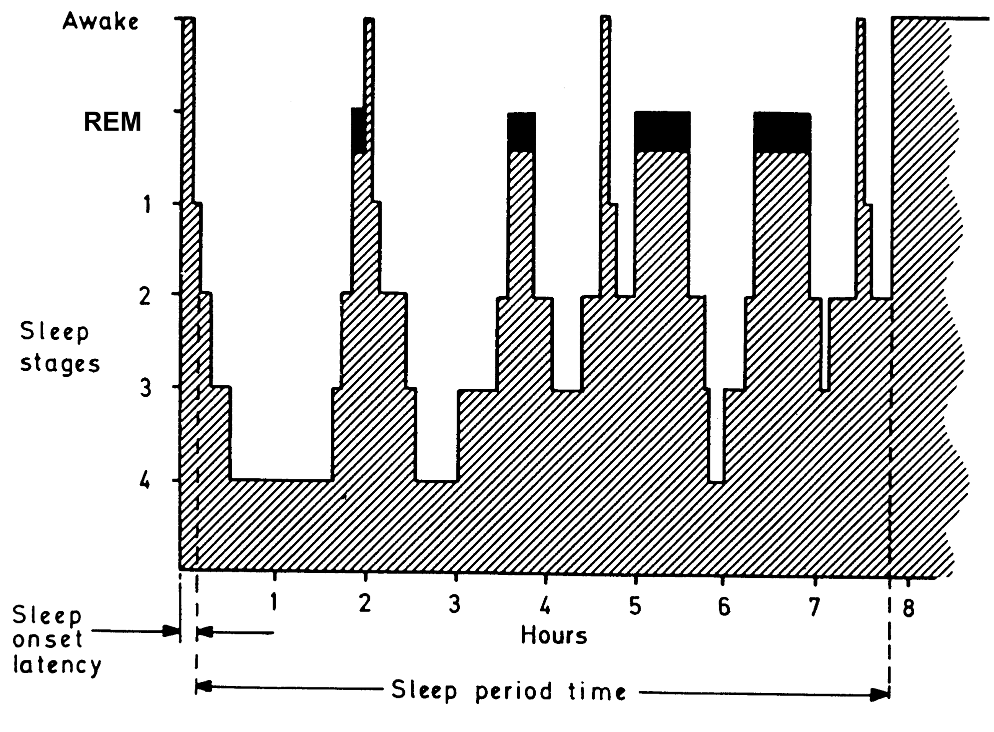

Figure A1 Typical Nocturnal Pattern of Sleep in a Young Adult

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Appendix B Scales

1 Samn-Perelli Seven-point Scale

Individuals are requested to select one statement that describes how they feel.

1 Fully alert; wide awake; extremely energetic

2 Very lively; responsive; but not at peak

3 Okay; somewhat fresh

4 A little tired; less than fresh

5 Moderately tired; let down

6 Extremely tired; very difficult to concentrate

7 Completely exhausted; unable to function effectively

2 Karolinska Sleepiness Scale

Individuals are requested to select a rating (including intermediate steps) that describes their level of sleepiness.

1 Very alert

2

3 Alert – normal level

4

5 Neither alert nor sleepy

6

7 Sleepy, but no effort to keep awake

8

9 Very sleepy, great effort to keep awake

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