European Union Aviation Safety Agency

This project has received funding from the European Union's Horizon Europe Programme

## EMCO SIPO EASA.2022.C17

## D-6 REPORT ON PILOT FATIGUE AND HUMAN PERFORMANCE

# eMCO-SiPO – Extended Minimum Crew Operations- Single Pilot Operations

An Agency of the European Union

**Disclaimer**



**DELIVERABLE NUMBER AND TITLE:** D-6.1 Report on pilot fatigue and human performance
**CONTRACT NUMBER:** EASA.2022.C17
**CONTRACTOR / AUTHOR:** NLR / A. van Drongelen
**IPR OWNER:** European Union Aviation Safety Agency
**DISTRIBUTION:** Public

| APPROVED BY: | AUTHORS | REVIEWER | MANAGING DEPARTMENT |
|---|---|---|---|
| | A. van Drongelen (NLR)<br>L. Marsman (NLR)<br>A. Karwal (NLR)<br>R. Simons (RS Consultancy) | J. Field (NLR) | A. Rutten (AOSH) |

**DATE: 22.02.2024**

# SUMMARY

The objective of the work described in this report was to assess by means of a literature review, how extended single-pilot operations during the cruise phase, combined with the assumed associated resting cycle as provided by the OEMs, would affect the alertness of the pilot-flying in terms of overall fatigue level and boredom, compared to today's two-pilot operations. In addition, the effects of in-flight rest during these operations and the possible differences as a result of using different types of in-flight rest facilities, were addressed. Since the 'proof of concept experiment' arising from this review will be combined with the experiment concerning Task 4 (regarding sleep inertia), more detailed recommendations regarding the optimal resting cycle, minimal rest facilities and maximum duty period, will be reported in a separate report.

Based on an extensive systematic literature search, 21 peer-reviewed articles of sufficient quality were found. These articles were complemented with ten grey literature reports. Taken together, the outcomes the literature suggests that time on task and length of the FDP, circadian pressure (time of day) and circadian disruption, the mount of pre-duty sleep, layover length, time since awake, the number of sectors flown, workload, medication and alcohol, aircraft cabin environmental conditions, pilot lifestyle and lifestyle, psychological factors, and individual variations are the most important factors for fatigue in long-haul operations.

The results of the articles that described the influence of (different types of) rest facilities on aircrew fatigue indicated that cockpit napping (e.g. by means of CR) is a quite common countermeasure of pilots to reduce their fatigue level. Sleep obtained on board can be sufficiently long when appropriate rest facilities are available and the seat/bed to sleep on allows pilots to lie in a (near) 'flat' position. It has also been found that in-flight sleep can be of lower quality and therefore has a lower recovery value as well. Next to seat/bed recline, circadian phase, flight characteristics, and individual factors, the level of sleep quality and quantity could also be affected by environmental factors (e.g. light and noise levels, warmth and dryness of cabin air) and psychological factors (e.g. difficulty taking one's mind off the flight). None of the articles retrieved adequately assessed the influence of being alone in the cockpit for an extended period of time during reduced crew operations. Hence, important differences between the effects of current long-haul operations and that of extended minimum crew operations, could occur. Factors such as a pilot's circadian rhythm, workload, and time on task may substantially differ from current operations, potentially affecting the build-up of fatigue. Furthermore, sleep inertia, being "on-call" while taking in-flight rest, and adequate effective mitigation strategies need to be addressed in future research, as very little empirical evidence is currently available.

To conclude, the conditions during a reduced crew scenarios are difficult to compare with the current long-haul working conditions with planned rest periods, ample time to wake up after a rest period, and a minimum of two pilots in the cockpit. In addition, the current literature does not allow to draw conclusions about the effects of monotony and boredom, in-flight sleep/sleep inertia, and scheduling factors (e.g. duty length, time of day, level of fatigue at start of duty etc) on the fatigue and alertness levels during different reduced crew operations. The available scientific knowledge about long-haul operations and its effect on fatigue and alertness cannot be translated to minimum crew operations, and these should be further investigated first. In addition, the most optimal rest/wake ratio for reduced crew operations is not clear. Future studies should therefore also incorporate multiple realistic rest/wake ratio scenarios, taking into account specific eMCO related factors such as noise of the PF engaged in flying tasks, timing, and personal characteristics. By means of this research, reliable results regarding sleep and fatigue during reduced crew operations would be acquired, and making it possible to get a more clear indication of applying the current FTL rules in eMCO operations as well.

# CONTENTS

SUMMARY .................... 3
CONTENTS 4
ABBREVIATIONS 5
1. Context .................... 6
1.1 Background 6
1.2 Scope of the document 6
2. Objective .................... 7
3. Approach .................... 8
3.1 Peer-reviewed literature search 8
3.1.1 Analysis 8
3.2 Grey literature search 10
4. Results of the literature review .................... 11
4.1 Literature search 11
4.1.1 Peer-reviewed literature 11
4.1.2 Grey literature 13
4.2 Data extraction and synthesis 23
4.2.1 Fatigue factors in long-haul operations 23
4.2.2 Influence of (different types of) rest facilities 25
4.2.3 Differences between reduced crew and regular long-haul operations 27
5. Gap analysis .................... 29
6. Discussion and conclusion .................... 32
7. References .................... 34

# ABBREVIATIONS

| ACRONYM | DESCRIPTION |
|---|---|
| A/C | Aircraft |
| ATC | Air Traffic control |
| CAT | Commercial Air Transport |
| CONOPS | Concept of Operations |
| CR | Controlled Rest |
| DBL | Deep Blue |
| DLR | German Aerospace Centre |
| EASA | European Union Aviation Safety Agency |
| eMCO | Extended Minimum Crew Operations |
| FDP | Flight Duty Period |
| HF | Human Factors |
| HMI | Human Machine Interface |
| ICAO | International Civil Aviation Organisation |
| NA | Not Applicable |
| NASA | National Aeronautics and Space Administration |
| NCO | Normal Crew Operations |
| NLR | Royal Netherlands Aerospace Centre |
| OEM | Original Equipment Manufacturer |
| PF | Pilot Flying |
| PM | Pilot Monitoring |
| PSG | PolySomnoGraphy |
| PVT | Psychomotor Vigilance Task |
| PR | Pilot Resting |
| RCO | Reduced Crew Operations |
| SA | Situational Awareness |
| ToD | Top of Descent |
| WOCL | Window of Circadian Low |

# 1. Context

## 1.1 Background

Due to the ongoing developments in technology, automation and autonomous unmanned aircraft, combined with the outlook of worldwide pilot shortage, there is an interest and desire to explore whether it is feasible to operate commercial air transport (CAT) with reduced flight crews in large aeroplanes. This feasibility needs to be considered from both the safety as well as efficiency perspectives.

Current legislation, as stated in both Air Operations Regulations as well as Certification Standards, require a minimum crew of two pilots:

- ORO.FC.200 states that aeroplane operations under instrument flight rules (IFR) or at night with a turbo-propeller aircraft with a minimum seating capacity of more than nine, or a turbojet aircraft, requires a minimum flight crew of two pilots.
- CS25.1523 states that the minimum flight crew must be established so that it is sufficient for safe operation. Although the Certification Standards therefore do not explicitly state that two pilots are required, all current aircraft regularly used in CAT are certificated for operation with a minimum crew of two pilots.

EASA was approached by aircraft manufacturers regarding the regulatory and safety aspects of such new concept of operations (CONOPs). Two specific CONOPs were identified:

- Extended Minimum-Crew Operations (eMCOs) are defined as operations with one pilot at the controls for extended periods during the cruise flight phase, while the other pilot(s) are resting; however, offering at least an equivalent overall level of safety through compensation means (e.g. ground assistance, advanced cockpit design with workload alleviation means, pilot incapacitation detection, etc.). It is, in particular, relevant to large aeroplanes operated in CAT operations, for which no fewer than two flight crew members are currently required as per the Air Operations Regulations.
  The concept of eMCO is also commonly referred to as *Reduced Crew Operations* (RCO). In this report where relevant the terminology "eMCO" will be used, but this must be regarded as interchangeable with the term "RCO".

- Single-Pilot Operations (SiPOs) are defined as end-to-end single-pilot operations. Annex III (PART-ORO) 'Organisation requirements for air operations' to the Air Operations Regulation already foresees conditions and limitations under which these types of operations are allowed. In the future, it is expected that these conditions and limitations will need to evolve in order to extend single-pilot operations to large aeroplanes, provided that compensation means (e.g. ground assistance, advanced cockpit design with workload alleviation means, capability to cope with pilot incapacitation, etc.) are in place in order to provide for at least an overall level of safety equivalent to today's two-pilot operations.

## 1.2 Scope of the document

The current Task 6.1 report synthesises the results of a literature review regarding the possible impact of extended minimum crew operations on fatigue risk and human performance only. Since the 'proof of concept experiment' will be combined with the experiment that addresses the research questions arising from Task 4 (regarding sleep inertia), more detailed recommendations regarding the optimal resting cycle, minimal rest facilities and maximum duty period, will be reported in a separate report (D-6.2).

# 2. Objective

Although the physiological and psychological effects of long (multiple hour) minimum crew operations in the context of large CAT aircraft are not entirely known, it could be expected that such operations may typically impact the level of fatigue and boredom of the pilot, negatively affecting their performance, especially during the single-pilot portion of the flight. Therefore, the objective of this task was to assess how extended single-pilot operations during the cruise phase, combined with the assumed associated resting cycle as provided by the OEMs would affect the alertness of the pilot-flying, in terms of overall fatigue level and boredom, compared to today's two-pilot operations. In addition, this literature review will address the effects of in-flight rest during these operations and the possible differences as a result of using different types of in-flight rest facilities, including rest in the cockpit seat.

*A practical definition of pilot fatigue, which is presently generally accepted in the aviation community, is formulated by the International Civil Aviation Organisation (ICAO, 2011), who defined pilot fatigue as "a physiological state of reduced mental or physical performance capability resulting from sleep loss or extended wakefulness, circadian phase, or workload (mental and/or physical activity) that can impair a crewmember 's alertness and ability to safely operate an aircraft or perform safety related duties".*

*High levels of pilot fatigue are considered to reduce flight safety levels because the cognitive symptoms of fatigue include: reduction in speed and accuracy of performance , lapses of attention and vigilance, delayed reactions. impaired logical reasoning and decision-making (including a reduced ability to assess risk or appreciate consequences of actions), and reduced situational awareness (Petrie & Dawson, 1997; Co et al., 1999; Caldwell & Gilreath, 2002).*

# 3. Approach

Our approach in this task involved a literature review (both peer-reviewed and grey literature) to assess the known physiological and psychological effects of long (multiple hour) single-pilot operations, potentially resulting in fatigue, boredom, alertness and reduced performance. In addition, the influence of different types of in-flight rest facilities (currently under CS FTL.1.205 identified as Class 1 to Class 3) on the quality of rest and the subsequent fatigue levels was assessed, and the possible consequences for the maximal flight duty periods were considered. In addition, the issues and elements that are not yet covered in literature were identified using a gap analysis. The results will be evaluated and summarized in the context of the SiPO and eMCO operation: what is the specific relevance of the findings for these types of operations, and do the findings have an effect on the current limits regarding flight duty periods for a two-pilot crew?

## 3.1 Peer-reviewed literature search

To obtain the current state of knowledge regarding the effects of long single-pilot operations and the influence of different types of in-flight rest facilities, a systematic search was conducted in the electronic database PubMed, ScienceDirect, PsycNET.

A so-called PICO strategy (Patient, Intervention, Comparison and Outcome) was composed, making sure the relevant characteristics of the population (e.g. airline pilots, cockpit crew), intervention (e.g. long duties, single pilot operations, in-flight rest), comparison (e.g. short-haul, multi-crew operations), and outcomes (e.g. fatigue, boredom, alertness) were added as search terms. The PICO strategy applied can be seen below:

**P**: Flight crew, airline crew, aircrew, cockpit crew, cabin crew, airline pilot, cat pilot, cargo pilot, pilots of airlines, aircraft pilot, commercial pilot
**I**: long duties, long-haul, ultra-long duties, ultra-long haul, extended duties, single pilot operation, reduced crew operation, in-flight rest, rest facilities, bunk, cockpit seat, controlled rest
**C**: NA
**O**: fatigue, boredom, drowsiness, sleep, attention, sleepiness, alertness, performance, vigilance

Inclusion criteria used were the following:
- language: English, French, German and Dutch only.
- publication date: no restrictions
- publication type: peer-reviewed articles only (no books / conference papers etc)
- sector: both military and civil aviation studies were included
- type of study: both lab and field studies

In order to find additional relevant studies based on the initial outcomes, the research team also screened the reference lists of all articles eligible for full-text screening (snowball sampling).

### 3.1.1 Analysis

#### 3.1.1.1 Article selection

In the first step, the titles and abstracts of the articles that resulted from the search strategy were independently screened for relevance by two authors (AD&LM). During the abstract screening only articles in which data was presented about fatigue or a fatigue related outcome (fatigue, boredom, alertness and performance) of aircrew were included. In addition, the exposure should reflect some sort of (ultra) long-haul flight duty, and/or describe the effects of resting facilities during the duty. Literature on fatigue during short-haul operations was not taken in consideration because eMCO concerns long-haul operations of which work schedules, workload, and stress levels are considered to be incomparable with short-haul operations in which flying multiple sectors, short turn-around times, and delays are found to be major factors causing fatigue and stress (Powell et al., 2007).

Furthermore, measurements of the fatigue outcome had to take place during the flight duty or just before/after the duty (and/or before/after the rest period). Information about the flight duty length should be provided as well. In case the article concerned in-flight or controlled rest, information about the length of the rest should be provided. Disagreements in the abstract appraisal were resolved by including all articles that were deemed eligible by at least one of the authors.

In the second step of the article selection procedure, the full texts of the remaining articles were retrieved, and independently screened by the same two authors (AD&LM). Disagreements for inclusion were resolved during a consensus meeting with these authors.

#### 3.1.1.2 Data extraction

Once the final set of articles were selected, the papers were systematically assessed, extracting the following information:

- Authors
- Year of publication
- Country
- Type of study (e.g. cross sectional, case-control, observational, intervention)
- Number of participants
- Function of the participants (e.g. pilots, cabin, other)
- Main fatigue related outcome measure
- Other variables taken into account (e.g. exposure, confounders)
- Main outcomes / conclusion(s)
- Study quality (good, fair, or poor)

Study quality was determined by means of the NIH Study Quality Assessment Tools. These tools are being used and recommended in studies in different research domains (e.g. Almufarrij et al. (2020)[1]; Godos et al. (2021)[2]; Ma et al. (2018)[3]). The advantage of this quality assessment is that it is applicable for each type of study (e.g. cross sectional, case-control, observational, intervention) and that the tools are based on quality assessment methods, concepts, and other tools developed by renowned researchers and epidemiologists working in evidence-based medicine. The tools therefore include items for evaluating potential flaws in study methods, including sources of bias (e.g., performance, attrition, and detection), confounding, study power, the strength of causality in the association between interventions and outcomes, and other factors. Quality reviewers can

[1] Almufarrij, I., Uus, K., & Munro, K. J. (2020). Does coronavirus affect the audio-vestibular system? A rapid systematic review. International Journal of Audiology, 59(7), 487–491.
[2] Godos, J., Grosso, G., Castellano, S., Galvano, F., Caraci, F., & Ferri, R. (2021). Association between diet and sleep quality: A systematic review. Sleep Medicine Reviews, 57, 101430.
[3] Ma, Y., Wei, F., Nie, G., Zhang, L., Qin, J., Peng, S., Xiong, A., Zhang, Z., Yang, X., Peng, D., Wang, M., & Zou, Y. (2018). Relationship between shift work schedule and self-reported sleep quality in Chinese employees. Chronobiology International, 35(2).

select "yes", "no", or "cannot determine/not reported/not applicable" in response to each item on the tool, which leads to an eventual quality appraisal of either ‘good’, ‘fair’, or ‘poor’. In order to determine a state-of-the-art on the current level of knowledge regarding fatigue in long-haul operations and the effects of rest opportunities, data of studies that were rated as being ‘good’ or ‘fair’ were extracted only.

## 3.2 Grey literature search

In addition to the systematic literature search on peer-reviewed articles, the ‘grey’ literature was assessed as well. Grey literature is research material by organizations outside of the traditional commercial or academic publishing and distribution channels. It can include, amongst others, theses, dissertations, research and committee reports, government reports, conference papers, and ongoing research. The ECASS consortium (European Committee on Aircrew Scheduling and Safety) for instance has studied over 4000 pilots during various rosters and operational conditions to develop a large database on all fatigue- and sleep-related aspects of short- and (ultra) long-haul operations, while the outcomes have not been published in peer-reviewed papers. For this study, only reports published by national and international aviation authorities, large research organisations, and specialised university departments were included.

The following search terms were used in Google Scholar to find relevant grey literature:

- pilot fatigue, alertness, performance
- monotony
- sleep
- onboard sleep, in-flight sleep, bunk sleep
- cockpit naps
- pre-duty sleep
- night flights, daytime flights, early morning flights
- long-haul operations
- circadian phase
- flight time limitations.

Inclusion criteria used were the following:

- language: English, French, German and Dutch only.
- publication date: no restrictions
- publication type: review (containing relevant data collected during long-haul flights)
- sector: civil air transport
- type of study: field studies

Where relevant, additional full-texts of peer-reviewed articles, found in the references of the selected grey literature were analysed (snowball sampling).

Since grey literature is per definition non-peer reviewed, it cannot be independently determined if the findings of these papers were based on objective and unbiased research. The quality of the grey literature can therefore not be appreciated as high quality, and were therefore appraised as being of ‘fair’ or ‘poor’ quality. For the data extraction, only grey literature reports of ‘fair’ quality were used.

After the data extraction of both the peer-reviewed and grey literature, the results were synthesized and presented together.

# 4. Results of the literature review

## 4.1 Literature search

### 4.1.1 Peer-reviewed literature

The results of the peer-reviewed literature search strategy can be found in Figure 4-1. The search resulted in 823 abstracts to be screened. As a result of the independent review by two of the authors, 731 articles were excluded because of the criteria described in section Article selection3.1.1.1. In total, 55 articles remained eligible for full-text screening. Of those 55, the consensus meeting between the authors resulted in 26 articles that were selected for data extraction. These 26 articles are listed in the Chapter 0 (In this report a literature

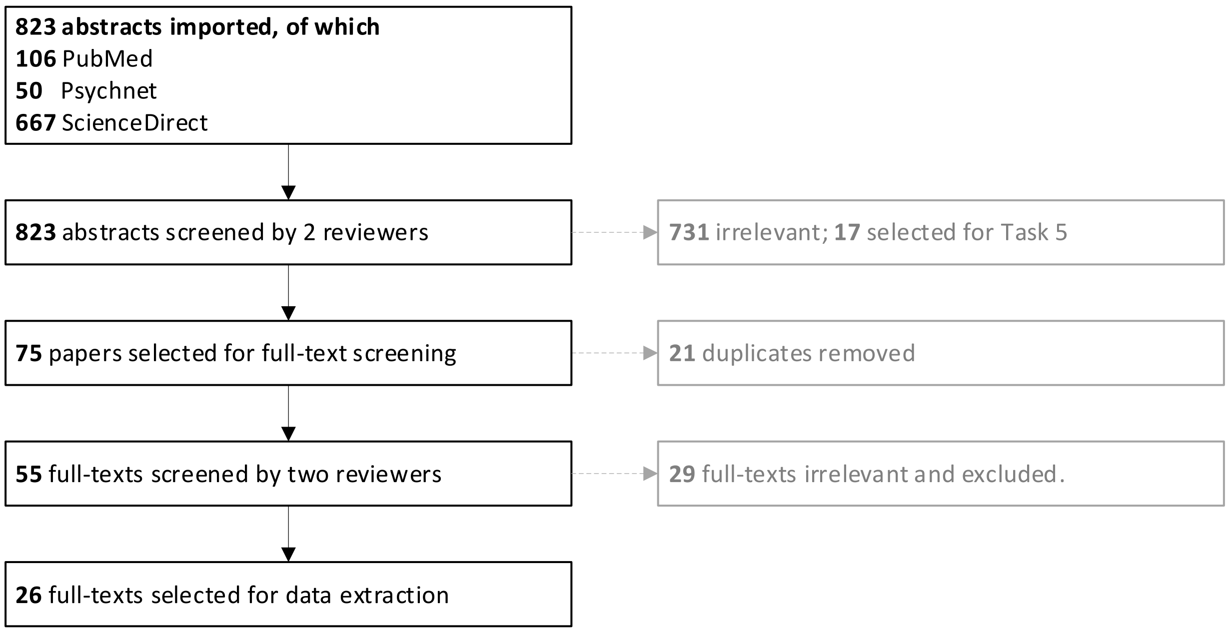


*Figure 4-1. Process selection peer reviewed literature*

review was conducted in order to assess the known physiological and psychological effects of long single-pilot operations, on fatigue, boredom, alertness and performance. Moreover, the influence of different types of in-flight rest facilities on the quality of rest and subsequent fatigue levels was investigated. The aim was to identify issues and elements of long single-pilot operations that are not yet covered in the current literature, by means of gap analysis.

The peer-reviewed literature search brought forward 21 articles of sufficient quality, which was supplemented with ten grey literature reports. Taken together, the outcomes of this literature suggests that time on task and length of the FDP, circadian pressure (time of day) and circadian disruption, the mount of pre-duty sleep, layover length, time since awake, the number of sectors flown, workload, medication and alcohol, aircraft cabin environmental conditions, pilot lifestyle and lifestyle, psychological factors, and individual variations are important factors for fatigue in long-haul operations.
Nine peer-reviewed and eight grey literature papers described the influence of (different types of) rest facilities on aircrew fatigue. The results of these articles indicated that cockpit napping (e.g. by means of CR) currently is a common countermeasure of pilots to reduce their fatigue level, and that sleep obtained on board can be quite good when appropriate rest facilities are available. It has been shown that a seat or bunk needs to allow

a pilot to lie sufficiently flat, though the size of the bunk/seat seems to be of lower importance. While in-flight sleep was shown to be able to lead to similar sleep duration in comparison to sleeping at home or in a hotel, sleep quality seems to suffer, with in-flight sleep being of lower recovery value, and having more frequent awakenings during the sleep period. Next to timing (circadian phase), flight characteristics, seat/bed recline, and individual factors, the level of sleep quality and quantity was also shown to be able to be affected by environmental factors (e.g. light and noise levels, warmth and dryness of cabin air) and psychological factors (e.g. difficulty taking one's mind off the flight).

None of the articles retrieved adequately assessed the influence of being alone in the cockpit for an extended period of time during reduced crew operations. Hence, important differences between the effects of current long-haul operations and that of extended minimum crew operations, could occur. Factors such as a single pilot's circadian rhythm, workload, and time on task may substantially differ from current operations, potentially affecting the build-up of fatigue. Furthermore, sleep inertia, being "on-call" while taking in-flight rest, and adequate effective mitigation strategies need to be addressed in future research, as very little empirical evidence is currently available. Some of these research questions will be addressed in the Task 4&6 sleep inertia, pilot fatigue and boredom experiments that will be conducted within the scope of the current project.

Taken together, the conditions during a reduced crew scenario such as eMCO are difficult to compare with the working conditions of regular long-haul or ultra-long range flights which use planned rest periods, can rely on augmented pilots having ample time to wake up, and always have two pilots in the cockpit. The available scientific data on the effects of current long-haul operations on fatigue and alertness can therefore not be translated to minimum crew operations yet, because especially the expected level of fatigue of the pilot flying (e.g. during less favourable times of day) should be further investigated first. In addition, the available data of regular long-haul operations do not allow to draw conclusions about effects of monotony and boredom, in-flight sleep and sleep inertia, and circadian factors on fatigue and alertness levels during different reduced crew circumstances (e.g. duty length, time of day, level of fatigue at start of duty etc). Other factors to be addressed are the (assessment of the) cognitive performance of the pilot resting when resuming duty, and potential effective mitigation strategies targeting either the individual pilot or the cockpit environment.

Based on the existing scientific literature, it remains unknown what the most optimal rest/wake ratio for reduced crew operations would be. Next to the research topics addressed above, future studies should incorporate multiple realistic rest/wake ratio scenarios in (simulated) reduced crew operation, implementing the proposed rest period of 2.5 hours, and taking into account the specific eMCO related factors (e.g. noise of PF engaged in flying tasks, timing, personal characteristics). By doing so, reliable results regarding sleep quality and length in the proposed cockpit seats would be acquired, and assumptions could be made about the fatigue levels (and thus levels of safety) during eMCO scenarios using the current FTL rules. Although OEMS have indicated that the benefits related to eMCO in-flight rest opportunities could potentially lead to extension of these rules, there is currently no data available to substantiate these assumptions.

References).

Two separate tables were created as a basis for data extraction: one about the effects of long-duty operations (Table 4-1) and one about rest facilities (Table 4-2). Of the 26 selected papers, 22 were about the effects of long-haul operations and ten about rest facilities (six papers addressed both topics).

### 4.1.2 Grey literature

The analysed grey literature is presented in Table 4-3. In total, ten reports were deemed of sufficient quality for data extraction. The statements below are based on these reports, and substantiated with references of peer-reviewed articles where possible. It is noteworthy that most “grey reports” were published around the turn of the last century, because at that time pilot fatigue was a hot topic and the usefulness of mitigation methods, such as onboard sleep, cockpit napping, and crew augmentation, was evaluated by multiple airlines and (inter)national authorities.

*Table 4-1.Characteristics of selected peer-reviewed articles about the effects of (ultra) long-haul operations.*

| Authors | Year | Country | Type of study | Number of participants | Function of participants | Main outcome measure | Other variables | Main outcomes / conclusions | Study quality |
|---|---|---|---|---|---|---|---|---|---|
| Cabon et al | 1993 | France | Observational / field study | 41 | Pilots | EEG, EOG, Actigraphy | | Only individual data reported; no aggregate data | Poor |
| Coombes et al | 2020 | United Kingdom | Observational / field study | 294 | Pilots | KSS, BALPA 2-way app | Roster variables | A quarter of all FDPs were predicted to be preceded by a main sleep of less than 6 hours, and 10% of all flying hours were associated with elevated fatigue risk levels. Per 1000 flying hours, 7.3 involuntary sleeps were reported | Fair |
| Gander et al | 2016 | USA & New Zealand | Observational / field study | 39 | Pilots | Actigraphy, KSS, SP, 5-minute PVT | Sleep diary | Pilots obtained more in-flight sleep on the first flight of the sequence than the 3rd for East Coast USA to Japan flights. The relief crew at landing also obtained more sleep than the commanding crew during their breaks. On the return flights (Japan - East Coast USA) no differences were found. | Fair |
| Gregory et al | 2021 | USA | Observational / field study | 500 | Pilots | Survey at TOD, with sleep diary, SP, KSS | Flight duty and pilot information | The second in-flight rest break was similar to the third on a range of outcomes relating to alertness. Compared to the third break, pilots reported better sleep quality and fewer disruptions during the second break. Both breaks decreased fatigue and sleepiness levels. Pilots taking the second break were significantly less fatigued at TOD compared to pilots taking the third break. | Fair |
| Hilditch et al | 2020 | USA | Observational / field study | 44 | Pilots | Actigraphy | Sleep diary | Controlled rest was taken in 46% of flights assessed, and resulted in sleep in 80% of cases. It happens most often in two-pilot crews during flights of less than 10 hours, and during night-time when flying back to base. Direction of travel was not found to be significant. | Fair |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Holmes et al | 2012 | Qatar | Observational / field study | 44 | Pilots | Actigraphy, KSS | Sleep diary | Sleep during ultra-long range flights did not exceed a KSS score of 5, and mean daily sleep duration was maintained above 6.3 hours. During in-flight rest, 98% of pilots obtained sleep, which was effective in reducing sleepiness. During layovers, 64% of pilots, and pilots from a culture in which siestas are common reported more naps than others | Good |
| Honn et al | 2016 | USA | Experimental / lab study | 24 | Pilots | PVT, KSS, SP | Manipulation: number of segments (multi, one) | With a multi-segment day, there is greater built-up of fatigue than with a single-segment day (with duty start time and duration held constant). Flight performance was not significantly reduced. | Good |
| Powell | 2008 | New Zealand | Observational / field study | 3023 | Pilots | SP | Flight and duty characteristics | Time of day, length of duty, number of sectors and type of duty (outbound or inbound) all contributed significantly to fatigue at ToD, with time of day being the strongest factor. The effect of length of duty depended on the time of day at ToD: the latter affects the overall level of fatigue at the start of duty but also the rate at which fatigue increases. | Fair |
| Powell | 2011 | New Zealand | Observational / field study | 4629 | Pilots | SP | Flight characteristics | Fatigue ratings were sensitive to the number of crew, time of day and circadian disruption. Fatigue ratings of two-person crews were comparable, and no average fatigue rating on any route exceeded 5. Fatigue seemed to increase with an increase in duty length, and long-haul night time duties were more fatiguing then out-and-back daytime duties. | Fair |
| Roach & Dawson | 2012 | Australia | Observational / field study | 19 | Pilots | SP, actigraphy, PVT | Layover length | Pilots with a shorter layover in the middle of their trip experienced higher subjective fatigue levels and worse sustained attention compared to pilots with a longer layover | Fair |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Roach et al | 2010 | Australia | Observational / field study | 301 | Pilots | SP (in sleep diary) | Actigraphy | A similar amount of sleep is obtained between in-flight sleep and matched bed sleeps, though it only results in 70% recovery | Fair |
| Roach et al | 2011 | Australia | Observational / field study | 301 | Pilots | Actigraphy | Duty diary and sleep diary | Duration of the duty period had a significant effect on the amount of sleep obtained, with the amount of sleep increasing as the duty period increased. Moreover, the percentage of rest time converted to sleep increased as the duration of a FDP increased. | Fair |
| Russo et al | 2005 | United States | Experimental / lab study | 8 | Military pilots | PVT | Motor performance | Acute sleep deprivation degrades visual perceptual, complex motor and simple motor performance | Fair |
| Sallinen et al | 2017 | Finland | Observational / field study | 86 | Pilots | KSS, actigraphy | Sleep diary | Long-haul FDPs covering the whole night were associated with a reduced sleep-wake ratio and alertness. During the same FDPs pilots also used more effective on-duty alertness management strategies. Finally, the frequency of reduced subjective alertness depended on how alertness was measured | Good |
| Sallinen et al | 2018 | Finland | Observational / field study | 51 | Pilots | KSS, actigraphy | Alertness management strategies diary, sleep diary | Pilots who indicated to be never sleepy achieved 54 minutes more sleep than those who indicated to be regularly sleepy on outbound flights. On inbound flights, this difference was 1 hour 23 minutes. | Good |
| Sallinen et al | 2020 | Multiple | Observational / field study | 392 | Aircrew and cabin crew | KSS at TOD, actigraphy | Sleep diary | The probability of high fatigue at TOD was higher during long FDPs at night compared to short night FDPs, but still higher than day FDPs (reference). Fatigue was best predicted by encroachment of the window of circadian low and by prior sleep. For night duties, the highest probability of fatigue was when the FDP covered the entire WOCL. | Good |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Sallinen et al | 2021 | Finland | Observational / field study | 86 | Pilots | KSS, actigraphy | Sleep diary | On-duty sleepiness was most frequently reported after inadequate sleep or due to FDP timing, regardless of whether this was SH or LH. These reasons were most frequently reported during early morning and night FDPs. | Good |
| Samel et al | 1997a | Germany | Observational / field study | 22 | Pilots | EEG, ECG, Motor activity | Subjective ratings, sleep log, NASA-TLX | Two consecutive night duties resulted in 9.3 hours sleep loss, and during duties, an increasing level of fatigue was found. Fatigue was higher during the return flight and some pilots reported critical levels. During both night flights, but especially during the second night flight, motor and brainwave activity and heart rate indicated drowsiness. | Good |
| Samel et al | 1997b | Germany | Observational / field study | 25 | Pilots | EEG, ECG, EOG, actigraphy | Subjective (fatigue) ratings, sleep log, NASA-TLX | Fatigue ratings increased as the FDP got longer, and fatigue was higher towards the end of a long US-west coast day-flight and all night flights (in comparison to a day-time flight). One some return flights, fatigue was found to be critical. | Good |
| Seah et al | 2021 | Singapore | Observational / field study | 19 | Pilots | KSS, SP, PVT, actigraphy | Sleep logs, sleep quality indicators | The three-crew composition is not worse for fatigue, sleepiness and performance for long-haul flights. | Good |
| Wright & McGown | 2001 | United Kingdom | Observational / field study | 12 | Pilots | EEG, EOG, actigraphy, head movements, GSR | | EEG and EOG were modified by sleepiness, and skin resistance increased during sleep. Wrist activity and head movements were absent during sleep. The most feasible measure for an alertness alarm when pilots fall asleep was wrist activity. | Good |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Wu et al | 2018 | New Zealand | Experimental / lab study | 41 | Pilots | Actigraphy, 5-minute PVT, sleep diary | Manipulation: two different bunk conditions (lie-flat bunk, bunk tapered 9 inch from hip to foot) | The amount of sleep obtained in-flight and the reaction time at Top of Descent were the same when sleeping in the full and the tapered bunk | Good |

*Table 4-2. Characteristics of the selected peer-reviewed articles about the influence of different types of in-flight rest facilities*

| Authors | Year | Country | Type of study | Number of participants | Function of participants | Main outcome measure | Other variables | Main outcomes / conclusions | Study quality |
|---|---|---|---|---|---|---|---|---|---|
| Gander et al | 2016 | USA & New Zealand | Observational | 39 | Pilots | Actigraphy, KSS, SP, 5-minute PVT | Sleep diary | Pilots obtained more in-flight sleep on the first flight of the sequence than the 3rd for East Coast USA to Japan flights. The relief crew at landing also obtained more sleep than the commanding crew during their breaks. On the return flights (Japan - East Coast USA) no differences were found. | Fair |
| Gregory et al | 2021 | USA | Observational / field study | 500 | Pilots | Survey at TOD, with sleep diary, SP, KSS | Flight duty and pilot information | The second in-flight rest break was similar to the third on a range of outcomes relating to alertness. Compared to the third break, pilots reported better sleep quality and fewer disruptions during the second break. Both breaks decreased fatigue and sleepiness levels. Pilots taking the second break were significantly less fatigued at TOD compared to pilots taking the third break. | Fair |
| Hilditch et al | 2020 | USA | Observational | 44 | Pilots | Actigraphy | Sleep diary | Controlled rest was taken in 46% of flights assessed, and resulted in sleep in 80% of cases. It happens most often in two-pilot crews during flights of less than 10 hours, and during night-time when flying back to base. Direction of travel was not found to be significant. | Fair |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Holmes et al | 2012 | Qatar | Observational / field study | 44 | Pilots | Actigraphy, KSS | Sleep diary | Sleep during ultra-long range flights did not exceed a KSS score of 5, and mean daily sleep duration was maintained above 6.3 hours. During in-flight rest, 98% of pilots obtained sleep, which was effective in reducing sleepiness. During layovers, 64% of pilots, and pilots from a culture in which siestas are common reported more naps than others | Good |
| Roach et al | 2010 | Australia | Observational | 301 | Pilots | SP (in sleep diary) | Actigraphy | A similar amount of sleep is obtained between in-flight sleep and matched bed sleeps, though it only results in 70% recovery | Fair |
| Roach et al | 2011 | Australia | Observational | 301 | Pilots | Actigraphy | Sleep and duty diary | Pilots use in-flight napping as a fatigue countermeasure, but the amount of sleep obtained in-flight depends on how fatiguing their shift is thought to be, which was determined by pilots' sleep/wake behaviour prior to duty, the duty length and on time of day. | Fair |
| Roach et al | 2018 | Australia | Experimental / lab study | 6 | Healthy adults | Polysomnography , KSS, VAS, 10-minute PVT, light intensity | Manipulation: seat in three conditions (upright 20°, reclined 40°, flat 90°) | Both the quality and quantity of sleep was better when sleeping in the flat and reclined seats compared to the upright seat. The amount of sleep in the flat and reclined seats was the same, but resulted in less REM sleep. There was no significant difference in subjective sleepiness, alertness, vigilance or response time between the three conditions. | Good |
| Signal et al | 2013 | New Zealand | Observational | 21 | Pilots | Polysomnography | Actigraphy | In-flight sleep by pilots is of lower quality compared to sleep on the ground in a hotel during a layover: in-flight sleep was less efficient, it had more stage1/stage 2 sleep, more awakenings, and little slow wave sleep. In the first part of flight, less sleep was obtained compared to the last past of flight. | Good |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Wu | 2018 | New Zealand | Experimental / lab study | 41 | Pilots | Actigraphy, 5-minute PVT, sleep diary | Manipulation: two different bunk conditions (lie-flat bunk, bunk tapered 9 inch from hip to foot) | The amount of sleep obtained in-flight and the reaction time at Top of Descent were the same when sleeping in the full and the tapered bunk | Good |
| Zaslona et al | 2018 | USA | Observational | 291 | Pilots | Questionnaires: pilot perspectives on in-flight sleep, fatigue mitigation strategies | Sleep diary | In-flight sleep by pilots seems to be effective in reducing fatigue and well-utilised, and pilots' pre-flight strategies on managing fatigue depend on when they expect to go on break during flight | Poor |

*Table 4-3. Characteristics of the selected articles from the grey literature.*

| Authors | Year | Country | Type of study | Topic | N | Target population | Subjective fatigue measure | Objective fatigue measure | Other variables | Quality |
|---|---|---|---|---|---|---|---|---|---|---|
| Airbus: (Speyer & Mollard) | 2004 | France | Review of all data collected by Université René Descartes and Airbus | Alertness and onboard sleep | NA | Non-augmented and augmented long-haul crews | Subjective and objective data of 34 commercial flights to North America with non-augmented crew and 12 commercial flights to Asia with augmented crew (studies done by Université René Descartes, LAA, Paris | | | Fair |
| CAA-UK | 2003 | UK | Review | Effects of in-flight sleep and napping on fatigue | NA | Long haul aircrew | Literature review of Qinetiq and ECASS studies using subjective and objective measures | | | Fair |
| CAA-UK | 2005 | UK | Review of studies | Review of Aircrew Fatigue Research Undertaken on Behalf of the UK Civil Aviation Authority. | NA | Aircrew | Review of results of fatigue research in Aircrew performed by QinetiQ, (former) DERA , and RAF Institute of Aviation Medicine. | | | Fair |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ICAO | 2011 | Global | Review and recommendations | Fatigue Risk Management System (FRMS) – Implementation guide for operators | NA | Pilots and Flight Ops managers | NA | NA | NA | Fair |
| Rosekind et al. | 1994 | USA | Intervention/field study | Effects of 40-min Cockpit Rest on Crew Performance and Alertness | 21 | nonaugmented 3-person crews on long-haul flight operations. | In-flight fatigue and alertness ratings; sleep logs | continuous ambulatory recordings of brain wave and eye movement activity; reaction time/vigilance task. | EEG, wrist activity monitor | Fair |
| Simons et al. | 1994 | NL | Intervention/ field study - * within subjects design on 2 comparable routes | Effectiveness of onboard rest on performance and alertness | 16* | Augmented 3 and 4-person crews on long haul operations | Stanford Sleepiness Scale (SSS) | Multi-Attribute Task battery (MAT), Vigilance Task, Slow Eye Movements during Stare at the Dot test | EEG/EOG, Actigraphy, Bunk Sleep Questionnaire (BSQS) | Fair |
| Simons & Spencer | 2007 | NL | Review/ Modelling | Extension of flying duty period by in-flight relief | NA | Long-haul pilots on flights with crew augmentation | NA | NA | NA | Fair |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Simons & Valk | 1997 | NL | Intervention/field Study | Effects of 40-min Cockpit Rest on Crew Performance and Alertness | 59 | Non-augmented 3-persons crews flying North-Atlantics as scheduled in their regular duty roster | Stanford Sleepiness Scale (SSS) | performance of a vigilance dual-task (VigTrack) | wrist activity monitor, Sleep log, 5-point Nap Quality Scale | Fair |
| Spencer & Robertson | 1999 | UK | Field study | Effects of onboard rest and circadian factors on fatigue and performance | 53 | Non-augmented crews on 10-11 hr flights with departure times at 12 different times of day | Samn-Perelli (SP) scale | performance of sustained attention task | wrist activity monitor, sleep diary | Fair |
| Spencer & Robertson (ECASS) | 2004 | Singapore | Field Study | Alertness and onboard sleep of crews flying non-stop ultra-long range flights | 110 | Augmented crews flying ultra-long range: SIN-LAX-SIN | Samn-Perelli (SP) scale & Karolinska Sleepiness Scale (KSS) | Vigilance and tracking performance (VigTrack) | wrist activity monitor, sleep diaries | Fair |

## 4.2 Data extraction and synthesis

The results of both the peer-reviewed and grey literature were combined, and presented below. As can be seen in Table 4-1, most selected peer-reviewed papers dealt with the effects of long-haul (LH), or ultra-long-haul (ULH) operations. Most of the time there were always two pilots in the cockpit during these duties (for instance due to augmented crews). Out of the 22 articles, 21 were deemed of sufficient quality for the data extraction (in addition to the ten selected grey literature reports).

First the factors that influence fatigue in long-haul operations will be described (section 4.2.1). In section 4.2.2 the main outcomes of the data extraction regarding in-flight rest (facilities) during long-haul operations are presented. Finally, in section 4.2.3, the expected differences in fatigue and alertness between reduced crew and today's two-pilot operations are described.

### 4.2.1 Fatigue factors in long-haul operations

Fatigue of pilots on long-haul flights is considered to be dependent of a variety of factors that contribute to whether an individual experiences fatigue as well as to the severity of that fatigue. The major factors affecting fatigue include the following.

**Time on task / length of FDP**
The longer a pilot has continuously been flying without a break, the more likely he or she is to be fatigued (e.g. Folkard & Tucker, 2003; Spencer et al., 1998). In addition, the longer a Flight Duty Period (FDP) lasts, the higher the chance of high fatigue (Åkerstedt et al., 2021; Sallinen et al., 2017; Sallinen et al., 2020; Powell et al., 2011). Powell et al. (2008) and Samel et al. (1997b) both found that strength of the length of duty effect depended on the time of day at Top of Descent (ToD) in non-augmented crews.

**Circadian pressure (time of day) and circadian disruption (crossing time zones)**
Fatigue is, in part, a function of the phase of the circadian cycle. During night flights circadian sleep pressure is maximal and fatigue and sleepiness are most severe during the WOCL (Window of Circadian Low), the period between 2:00 AM and 6:00 AM (Åkerstedt et al., 1998; Spencer et al., 1998; ICAO, 2011). This was also found by Sallinen et al. (2020) and Powell et al. (2008; 2011): night flights encroaching the WOCL constituted the major cause of high fatigue. Gander et al. (2014) even suggested that flight timing (arrival/departure times) may be more important for fatigue and cognitive performance at ToD than flight duration. In addition, sleep quantity and quality can decrease as a result of circadian disruption (e.g. as a result of crossing time zones) which can in turn increase fatigue (e.g. Gander et al., 2016).

**Pre-duty sleep**
If a pilot has had less than seven hours of sleep in the past 24 hours, (s)he is more likely to be fatigued. Scientific research have consistently demonstrated that inadequate sleep increases on-duty sleepiness (e.g. Sallinen et al., 2021) and that sleep deprivation degrades visual, perceptual, complex motor, and simple motor performance (e.g. Coombes et al., 2020; Russo et al., 2005). Sleep opportunities during the WOCL are preferable because sleep that occurs during the WOCL provides the most recuperative value. Within limits, shortened periods of night-time sleep may be nearly as beneficial as a consolidated sleep period when augmented by additional sleep periods, such as naps before evening departures, during flights with augmented flight crews, and during layovers (Simons, 2017).

**Layover length**
Sleep length during layovers has been found to be associated with fatigue during the subsequent flight as well (Holmes et al., 2012). Samel et al. (1997a) found that a short (13h) layover in between two night non-

augmented night duties resulted in 9.3 hours sleep loss, and thus an increased level of fatigue during the return flight, sometimes reaching critical levels. Roach et al. (2012) indicated that pilots with a shorter layover in the middle of their multi-day duty period experienced higher subjective fatigue levels and worse sustained attention compared to pilots with a longer layover.

**Time since awake**
A pilot who has been continually awake for a longer period of time (e.g. 17 hours or more) since his or her last major sleep period is more likely to be fatigued (Vejvoda et al., 2014; Roach et al., 2011). In addition, cumulative sleep debt (limited sleep during multiple days) may lead to severe fatigue as well (Dinges et al., 1997).

**Number of sectors**
Honn et al. (2016) showed, in a high-fidelity simulator, that fatigue became higher during a long duty of nine hours, with multiple take offs and landings, in comparison with a single-segment duty day. The findings were directly attributable to the number of flight sectors flown. A more recent study by Sallinen et al. (2020) found that the number of sectors contributed only marginally to fatigue, especially in comparison with night flights encroaching the WOCL. Powell et al. (2007;2008) on the other hand found that number of sectors had one of strongest influences on fatigue, in 2-pilot crews in mixed SH and LH operations. Åkerstedt et al. (2021) found that the number of sectors predicted fatigue, but that this significant effect disappeared when FDP length was added to the multivariate analysis.

**Workload**
A high workload as well as a very low workload may contribute to fatigue. Long-haul cruise flights are for instance often monotonous which may lower the level of arousal and thus affect vigilance (Airbus, 2004).

**Medication and alcohol**
Sedative medications, such as antihistamines and benzodiazepines may contribute considerably to fatigue, lowered alertness, and increased sleepiness. The same holds for hangover effects of alcohol (Simons, 2017).

**Aircraft cabin environmental conditions**
The ambient pressure in the aircraft cabin may be as low as 0.75 atmosphere. The consequent increment of the partial oxygen pressure causes the oxygen saturation of the blood to decrease by 5-8%. Although there is no convincing evidence that this would affect cognitive functioning, this phenomenon may contribute to the feeling of weariness and subjective fatigue. This feeling might be further intensified by the low relative humidity prevailing in the cockpit. In addition, high ambient temperature, noise, and turbulence may also contribute to fatigue in sensitive individuals (Simons, 2017).

**Health and lifestyle**. A lack of physical exercise, unhealthy diet, and pre-duty rest all contribute to unfitness and a higher chance of in-flight fatigue (Simons, 2017).

**Psychological factors and life stress**
Life-stress, such as caused by work related problems, financial worries, health concerns, bereavement issues, relationship/family difficulties, separation from family, and social demands may also disrupt sleep, which in turn may lead to higher fatigue levels (Simons, 2017).

**Individual variation**
Individuals are affected by fatigue factors differently and may become fatigued at different times, and to different degrees of severity, under the same circumstances (Saksvik et al., 2011; van Drongelen et al., 2017).

### 4.2.2 Influence of (different types of) rest facilities

Of the nine articles about the effects of different types of rest-facilities, eight were deemed of high enough quality for the data extraction as shown below.

**Seat napping / Controlled Rest**

The quality and effect of sleep in the cockpit was discussed in two articles (Hilditch et al., 2020; Roach et al., 2018). Hilditch et al. (2020) studied the prevalence and characteristics of Controlled Rest (CR) by means of an observational study using 44 US-based pilots and equipping them with actigraphy. The pilots were found to use CR in 46% of flights, of which 80% resulted in actual obtained sleep, while also on 48% of flights bunk rest was taken. Only a minority of the pilots did not record any CR, indicating that CR is fairly common on the flight deck. Moreover, CR actually leads to effective sleep, with an average sleep duration of approximately 31 minutes per CR period, while the recommended maximum CR duration is 45 minutes in order to limit any actual sleep to approximately 30 minutes (GM1 CAT.OP.MPA.210). CR was used more frequently on non-augmented flights (69% vs 23%); night flights (55% vs 34%) and <10 h flights (63% vs 27% (>10 h)).

Roach et al. (2018) investigated the quality and quantity of sleep obtained in a seat with different back angles, 20° (upright), 40° (reclined), and 90° (flat) during a daytime nap by means of polysomnography (PSG). In their experiment with a small number of participants, they found a significant effect of back angle: the quantity and quality of sleep obtained in the reclined and flat seats were better than those obtained in the upright seat. Compared to the flat seat, the reclined seat resulted in similar sleep length, but lower quality (37% less Rapid Eye Movement (REM) sleep). The upright seat resulted in 29% less total sleep, 30% less slow-wave sleep, and 79% less Rapid Eye Movement (REM) sleep, compared to the flat seat. The authors indicate that it might be difficult to maintain the head in a comfortable position for sleep when sitting upright, while an upright posture increases a heightened level of physiological arousal. Important to note however is that after the sleep period, functional capacity tests, subjective sleepiness, subjective alertness, response speed and vigilance, were not significantly influenced by seat recline. However, in the study of Simons & Valk (1997) it was shown that 50% of the pilots could not sleep at all in an upright cockpit seat and the non-sleepers showed no beneficial effect on alertness after their cockpit nap. The authors therefore conclude that short cockpit naps should be considered as an emergency measure to prevent excessive fatigue, and not as a measure to extend flight time limitations.

To conclude, Controlled Rest seems to be applied quite regularly, and research shows that sleep can be obtained during these rest periods in an upright position in the cockpit, although sleep quality and quantity is suboptimal, and individual differences exist.

**Influence of in-flight rest facilities**

More both grey and peer-reviewed literature is available on the quality and restorative effect of separate rest facilities, e.g. in bunks, which are currently most often used for (scheduled) in-flight rest periods with augmented crews. Simons & Spencer (2007) summarized studies of sleep characteristics of augmented crew members that were carried out in bunks of different types of aircrafts (B747-400, MD 11, B777 and B777-200ER, Airbus 340-500). Objective and subjective monitoring demonstrated that, in most cases, the quality of sleep that aircrew achieved was relatively good: at times when the pilots were particularly tired, they managed to get lengthy periods of Slow Wave Sleep (SWS). In general, the studies established that there was no major problem with sleeping on aircraft, given the appropriate facilities. However it should be mentioned that during these augmented long-haul flights: 1) the pilot rest facilities were optimal (rest on horizontal bed in comfortable bunk), and 2) rest was scheduled, for which the augmented crew had no apprehension of "being on call", known to have negative effects on sleep.

Wu et al. (2018) indicated that bunks can be slightly tapered at the feet depending on the shape of the aircraft, which could affect the in-flight rest quality (Wu et al, 2018). In this study, 41 participants from New Zealand were randomly assigned to sleep in a tapered bunk instead of a regular one, while the amount of sleep obtained was monitored using actigraphy and sleep diaries. An average of 134 minutes (*SD* = 53) of total in-flight sleep in bunks was obtained. The results did not show any differences in total in-flight sleep, suggesting that a slightly smaller bunk at the feet will not affect the pilot's ability to sleep in-flight. In addition, no meaningful differences in performance, as measured by means of the Psychomotor Vigilance Task (PVT) at Top of Descent (TOD) was found between the two conditions.

Roach et al. (2010) studied 301 Boeing 747–400 airline pilots operating 4-crew long-haul flight patterns for at least two weeks using sleep diaries and actigraphy. The aircrafts were configured with two on-board rest facilities comprising a small self-contained space with a seat that converts to a flat bed. The results of the study indicated that sleep opportunities in on board rest facilities during long-haul flights led to a similar amount of sleep as during matched bed sleeps of similar duration at home. However, these in-flight sleep opportunities resulted in a 30% lower recovery value (calculated as the difference between self-rated fatigue at the start vs the end of the sleep period). These findings indicate that sleeping in on-board
rest facilities does not affect the amount of sleep obtained, but it can affect the degree of restoration provided by that sleep. Roach et al. (2011) used the results of this same study for another article, where they looked for the influence of fatigue likelihood on in-flight rest taken. The results showed that the level of fatigue experienced by the long-haul pilots substantially influenced the sleep onboard. When their fatigue likelihood was (very) high, more sleep during duty periods was obtained, in comparison with when fatigue likelihood was low. The amount of sleep obtained, and the percentage of inflight rest time spent sleeping, both increased: when fatigue was low, pilots converted 27% of their rest time to sleep, and when fatigue likelihood was very (high), pilots converted 54% of their rest time to sleep.

**Other factors**

Gander et al. (2016) measured in-flight sleep in 39 B747-400 pilots during a variety of long-haul trips between US and Asia with both 3- and 4-pilot crews. They found that the total in-flight sleep was affected by the level of circadian disruption experienced by the participants. Holmes et al. (2012) found similar results for ultra-long flights between Doha and Houston: the amount of in-flight sleep increased as a result of higher pre-duty fatigue levels, circadian disruption and the timing of the return flight. Furthermore, Signal et al. (2013) found in ultra-long-haul flights, that sleep during longer periods of in-flight rest was less efficient and contained more frequent awakenings per hour, compared to sleep in a hotel. Within 7-hour rest periods, on average 3.3 hours (SD = 1.3) of sleep was obtained by the pilots. However, while these findings do show that in-flight sleep is shorter than rest obtained in a hotel bed, only 67% of the time during a rest break, the pilots spent trying to obtain sleep. This could be caused by time of day, the pilot's circadian rhythm, and the subsequent sleep pressure as well. This finding was substantiated by Gregory et al. (2021) who found that during ultra-long haul flights, compared to the third break, pilots reported better sleep quality and fewer disruptions during the second break which was taken earlier during the flight. In addition, pilots taking the second break were significantly less fatigued at TOD compared to pilots taking the third break. In the grey literature reports, this "timing of in-flight sleep" factor was also found to be important. Pilots who had their (minimum) two hour rest period in the beginning of the flight - and therefore were not tired- showed a sleep efficiency (ratio total sleep time/ time in bed) of 30-48% while those who took the 2nd rest opportunity in the second half of the flight had an efficiency of 60-81% (Simons et al., 1994). Another, less studied factor that has been found to influence both in-flight sleep quantity and quality is age (more difficult to sleep efficient in-flight with higher age) (Signal et al., 2013).

The results of the studies described above show that in-flight sleep can be an effective fatigue countermeasure: sleep of sufficient duration can be recuperative and can improve alertness up to ToD. However, there is still room for improvement: other studies have shown that pilots can have difficulty converting time in on-board rest facilities into actual sleep. Besides the sleep/wake aspects, flight characteristics, seat/bed recline, and individual factors mentioned above, the authors indicated that this poor rate of sleep conversion can be attributed to a number of environmental factors (e.g. comfort of the bed, light and noise levels, warmth and dryness of cabin air, turbulence, etc.) and psychological factors (e.g. difficulty taking one's mind off the flight) associated with sleeping on-board an aircraft (Rosekind et al. 2000). However, more, higher quality research is still needed to determine the influence of all of these factors on the efficacy of both controlled and in-flight rest during real flights, and if the sleep obtained is sufficient to maintain crew alertness.

### 4.2.3 Differences between reduced crew and regular long-haul operations

The factors affecting fatigue mentioned in section 4.2.1 have all been studied in long-haul airline operations with a multi-pilot (augmented) cockpit crew. There have been some studies that focussed on non-augmented crew (e.g. Samel et al. 1997a;1997b; Powell et al., 2008;2011), and in some of these Controlled Rest (CR) caused a situation in which there was one Pilot Flying (PF) and one Pilot Resting (PR) (e.g. Rosekind et al. 1994; Simons & Valk, 1997; Hilditch et al., 2020) for a short period of time. It is should however be acknowledged that the findings of all studies described, and as such the found factors influencing fatigue, apply to long-haul operations in which there are two pilots in the cockpit during all phases of the flight. As a result, major knowledge gaps exist, and additional research is needed (as explained in the Gap analysis in the next chapter). However, when considering a PF in a reduced crew concept such as eMCO, and based on the findings described above, flying alone for 2 to 4 hours during cruise phase could lead to some distinct fatigue risks, while others will remain quite similar.

**Time on task**

A 2 to 4 hours' time on task period of a PF in a reduced crew concept is considerably shorter than the flight duty period of pilots in regular (non-augmented) long-haul flights (8-10 hours). As in augmented long-haul flights (with one or two extra flight crewmembers), the shorter time on task, as a result of in-flight sleep might mitigate fatigue levels in reduced crew operations. However, it has to be considered that the workload (e.g. single pilot flying, hand-over/take-overs) and rest characteristics (e.g. facilities, work/rest ratio) of flights with augmented crew could differ significantly from that of reduced crew operations for which this should first be further investigated.

**Circadian factors**

Circadian phase has been shown to have a profound influence on the time that a pilot is able to function, before her/his alertness decreases to an unacceptable level. Simons & Spencer (2007) showed that during a day flight, pilots reached 70% of their basic alertness score after 8.4 hours of flying, while during a night flight this reduced alertness level was already reached after 3.5 hours' time on task. Thus, for both the PF in reduced crew operations as for pilots on regular long-haul flights, sleep pressure during the WOCL may be overwhelming and may lead to micro-sleeps and lowered alertness. When there is one pilot in the cockpit the potential implications of such a potential safety critical situation could be different in comparison with regular operations.

**Amount of pre-duty sleep**

The importance of sufficient pre-duty sleep (7-8 hrs/24 hrs) is similar for the reduced crew operation crew members as for pilots flying on regular long-haul operations.

**Time since awake**

The effects of time since awake and cumulative sleep debt will be similar for the reduced crew operation crew members as for pilots flying on regular long-haul operations (pilots who have been continually awake for longer periods of time are more likely to become (critically) fatigued).

**Workload**

The workload of the single PF during cruise phase in a reduced crew concept might potentially be higher than that of pilots during a normal operation with at least two pilots flying. The workload could be either higher (e.g. in case of a non-nominal situation, or in conditions where multiple tasks must be performed that would normally be shared between PF and PNF) or lower (e.g. due to increased automation). In addition, the lack of professional and social interaction with a colleague pilot may lead to more monotony, boredom, and feelings of drowsiness. The scarce literature on boredom is based on subjective ratings only; objectively measured data of the level of boredom is not available. Boredom has been associated with a higher frequency of attention lapses (Bhana, 2009) and there is evidence that alertness decreases the most during the monotonous part of the cruise flight (Airbus, 2004). Therefore, both monotony and boredom can be considered as a potential problem during the cruise phase of reduced crew operations.

The effects of **medication**, **cabin environmental conditions**, **lifestyle, psychological factors and life stress** on fatigue are considered to be equally applicable to pilots in reduced crew operations as to pilots flying regular long-haul flights. It should be mentioned however that although the authors of some studies have recommended to use doses of 200-300 mg caffeine or 200 mg modafinil to enhance alertness and reduce sleepiness during (night) flights (e.g. Wingelaar-Jagt et al., 2023; Caldwell et al., 2009; Klopping et al., 2005), doses of 200 mg or more caffeine may cause adverse effects, such as tachycardia, arrhythmia, atrial fibrillation, anxiety, insomnia, increased urination, muscle twitches or tremors, irritability, agitation, and gastro-intestinal upset (Evans et al., 2023). Furthermore, excessive usage of caffeine can also negatively affect subsequent sleep (either during or after duty), which could lead to additional fatigue (e.g. Gardiner et al., 2023). Moreover, the effective dose of 200 mg modafinil may cause nausea, headache, diarrhoea, and hypertension in sensitive subjects (Greenblatt et al., 2023). Therefore, while its use might be acceptable in the military, using these pharmacological mitigations in such doses is unacceptable for fatigue mitigation in civil aviation in itself, and especially during reduced crew operations, in order to prevent incapacitation events.

# 5. Gap analysis

Based on the results of the literature review, this chapter describes the most profound knowledge gaps between regular and reduced crew operations. These gaps should be studied more thoroughly first, before conclusions can be drawn about the probability/severity of the fatigue risks, the feasibility, and safety of the proposed reduced crew operations.

It is should be acknowledged that the findings of all studies described, and as such the factors found to influence fatigue, apply to long-haul operations in which there are two pilots in the cockpit during all phases of the flight. The conditions of a reduced crew scenario such as eMCO are incomparable with the conditions on regular long-haul or ultra-long range flights which use planned rest periods and can rely on pilots having ample time to wake up.

**1. Sleep facilities**

As described by Simons & Spencer (2007), the characteristics of the sleep facilities are crucial for the quality of sleep and its subsequent recuperative value. Studies that showed the most positive effect of in-flight sleep in (ultra) long-haul operations concerned sleep taken in a separate, horizontal crew bunk, in which the conditions are as conducive to sleep as possible and comfort is optimal. These onboard sleep conditions are incomparable with the conditions on a horizontally positioned seat which is situated in the cockpit as foreseen in one of the eMCO scenarios. Although mitigating measures, such as noise reduction and eye shades can be used, sleep might potentially be disturbed by cockpit activities of the PF and other environmental disturbances. In addition, Simons & Valk (1997) found that 50% of the pilots could not sleep at all in a cockpit seat, for which no beneficial effects on alertness after the rest period occurred. It is therefore recommended to study the sleep quality and length in the newly proposed cockpit seats, during realistic flight duties. Both the effects on alertness and performance of these rest periods of about 2.5 hours, and the influence of different kinds of factors (e.g. noise of PF engaged in flying tasks, timing, personal characteristics) should be taken into account.

**2. Length of rest period**

In-flight sleep of sufficient duration and quality might be an effective tool to mitigate fatigue and reduced alertness of the PF during cruise phase of the flight and to optimise alertness and performance during approach and landing. In-flight sleep between 10 minutes (power naps) and four hours taken at any time of day or night is considered to be a beneficial countermeasure for fatigue and reduced alertness of pilots during regular long-haul flights (Simons et al., 1997; Spencer & Robertson, 1999; Robertson & Stone, 2002; Spencer & Robertson, 2004; Airbus, 2004). However, based on the literature described, it is unknown what the most optimal rest/wake ratio for reduced crew operations should be. Whereas longer rest periods would increase recovery of the PR, it would also increase the risk of more severe sleep inertia while it lays a higher burden on the PF (the longer the time flying alone, the higher the risk of high levels of fatigue due to monotony and/or increased time on task). Future research should therefore include studies of multiple realistic rest/wake ratio scenarios in (simulated) reduced crew operations.

**3. Maximal Flight Duty Period duration**

OEMS have indicated that the benefits related to the in-flight rest opportunities of their aircrafts could potentially lead to extension of the current FTL schemes.

About 20 years ago, based on the SAFE model and the ECASS/QinetiQ databases of onboard sleep and alertness, a model was developed to estimate the allowed FDP extension based on the duration of the rest period of augmented crew, the type of rest facility, and the continuous presence of two pilots on the flight deck (CAA, 2005; Simons & Spencer, 2007). For the fully acclimatized individual, and based on augmented crew sleeping in a bunk with horizontal rest facilities, it was advised to allow extension of the maximum permitted FDP with a period of time equivalent to 75% of the duration of the rest. This means that for a rest period of 2 hours of the acclimatized augmented crew member, the FDP could be extended by 90 minutes, while for an acclimatized individual it was 72 minutes (80% of the acclimatized extension). This is provided that the maximum FDP is 16 hours, and if augmentation is only by one additional pilot (Simons & Spencer, 2007). Current regulations allow for an increase of the FDP from a maximum of 13 hours to a maximum ranging between 14 and 18 hours depending on number of sectors, number of additional augmented crew members, rest facility class and flight time while prescribing a minimum in-flight rest period as a condition to extend the FDP (FTL 1.205).

However, these guidelines and regulations do not need to be applicable to reduced crew operations since in these operations the sleep facilities may be suboptimal, there is no augmented crew available, and there is only one pilot flying during cruise flight. Therefore, FTL extensions should only be made possible once the assumptions by the OEMs have been validated through solid scientific research. In addition, reduced crew scenarios need to be rolled out first, in order to assess through in-service experience whether the current FTL are safe for eMCO, before extensions of the limits should be considered.

### 4. Sleep quality of Pilot Resting

In reduced crew operations the Pilot Resting (PR) could be called to assist or replace the PF at any time in case of emergency or incapacitation; in other words s/he is 'on call'. Shift work related research has shown that both sleep quantity and quality (less SWS and REM sleep) of employees of safety sensitive jobs (e.g. medical, fire brigade) who are on-call can be impaired (Torsvall et al.,1989; Hall et al., 2017), for which recuperation is lower than expected/needed. This psychological factor related to reduced crew in-flight sleep should be studied thoroughly as well, as should possible mitigating measures and individual differences in sensitivity.

### 5. The effects of monotony/low workload

The alertness level of a subject can be greatly influenced both by the environment and by the activity of the subject himself. The environment and the type of task determine the degree of monotony of the situation as it can be defined as "the characteristics of a task in which the sensorial stimulations remain almost constant and extremely repetitive". Flying as a single pilot during the cruise phase of a flight might be monotonous due to the lack of communication with a colleague, the lack of external communication which is especially experienced by pilots crossing the Atlantic or Pacific Ocean, and the reduced number of tasks due to the increased level of automation. The literature described in this report showed that during night flights, when the circadian pressure to sleep is maximal, the combination with monotony might increase drowsiness towards critical (close to falling asleep) levels, and substantially degrade alertness and performance. The effects of such low workload flying tasks on a single PF should therefore be further investigated, during different circumstances (e.g. duty length, time of day, circadian disruption, level of fatigue at start of duty etc).

### 6. Take-over after a resting period

If the resting pilot takes over from the PF, sleep inertia has to be overcome, and it has to be defined when the individual sleep inertia period is considered to be sufficiently dissipated. The question is if this will for instance be done using a subjective alertness rating of the pilot concerned, or by means of an objective measurement of the level of cognitive functioning. This is important because there is evidence that after awakening, subjective alertness recovers faster than objective cognitive performance (Jewitt et al., 1999; Folkard & Åkerstedt, 1992; Hilditch & McHill, 2019). It might, therefore, be conceivable that the pilot who has to take over the PF task will mention that the sleep inertia is "over" while the cognitive function might still be impaired. Report D-4.1 within this project has shown that on average sleep inertia does not exceed more than 35 minutes. However, it is conceivable that after sleeping for two hours, and starting the PF duty during the Window of Circadian Low (WOCL between 02:00 and 05:59 hours in the time zone to which a crew member is acclimatised), physiological circadian sleep pressure might linger on after subjective sleep inertia seems to have dissipated and - in a monotonous environment with a lack of stimuli - sleep pressure might take over and may gradually cause sleepiness and reduced alertness. This theoretical concern lacks evidence because such a scenario has never been studied due to the fact that it does not exist in regular long-haul air transport. Therefore, additional research is necessary to study the combination of latent sleep tendency, circadian sleep pressure, and monotony on performance/fatigue after the resting period. Therefore, some of these research questions will be addressed in the upcoming sleep inertia, pilot fatigue and boredom experiments of both Task 4&6.

## 7. Mitigation strategies.

Based on the previous sections, several methods could be considered to mitigate fatigue risks in reduced crew operations. From the literature review in this report, it could be derived that these mitigating measures could for instance include coping strategies (e.g. sleep hygiene, nutrition, coffee), environmental cabin factors (light, noise etc) and/or education in stress reduction. None of these strategies have been studied on their effect in reduced crew operations.

# 6. Discussion and conclusion

In this report a literature review was conducted in order to assess the known physiological and psychological effects of long single-pilot operations, on fatigue, boredom, alertness and performance. Moreover, the influence of different types of in-flight rest facilities on the quality of rest and subsequent fatigue levels was investigated. The aim was to identify issues and elements of long single-pilot operations that are not yet covered in the current literature, by means of gap analysis.

The peer-reviewed literature search brought forward 21 articles of sufficient quality, which was supplemented with ten grey literature reports. Taken together, the outcomes of this literature suggests that time on task and length of the FDP, circadian pressure (time of day) and circadian disruption, the mount of pre-duty sleep, layover length, time since awake, the number of sectors flown, workload, medication and alcohol, aircraft cabin environmental conditions, pilot lifestyle and lifestyle, psychological factors, and individual variations are important factors for fatigue in long-haul operations.
Nine peer-reviewed and eight grey literature papers described the influence of (different types of) rest facilities on aircrew fatigue. The results of these articles indicated that cockpit napping (e.g. by means of CR) currently is a common countermeasure of pilots to reduce their fatigue level, and that sleep obtained on board can be quite good when appropriate rest facilities are available. It has been shown that a seat or bunk needs to allow a pilot to lie sufficiently flat, though the size of the bunk/seat seems to be of lower importance. While in-flight sleep was shown to be able to lead to similar sleep duration in comparison to sleeping at home or in a hotel, sleep quality seems to suffer, with in-flight sleep being of lower recovery value, and having more frequent awakenings during the sleep period. Next to timing (circadian phase), flight characteristics, seat/bed recline, and individual factors, the level of sleep quality and quantity was also shown to be able to be affected by environmental factors (e.g. light and noise levels, warmth and dryness of cabin air) and psychological factors (e.g. difficulty taking one's mind off the flight).

None of the articles retrieved adequately assessed the influence of being alone in the cockpit for an extended period of time during reduced crew operations. Hence, important differences between the effects of current long-haul operations and that of extended minimum crew operations, could occur. Factors such as a single pilot's circadian rhythm, workload, and time on task may substantially differ from current operations, potentially affecting the build-up of fatigue. Furthermore, sleep inertia, being "on-call" while taking in-flight rest, and adequate effective mitigation strategies need to be addressed in future research, as very little empirical evidence is currently available. Some of these research questions will be addressed in the Task 4&6 sleep inertia, pilot fatigue and boredom experiments that will be conducted within the scope of the current project.

Taken together, the conditions during a reduced crew scenario such as eMCO are difficult to compare with the working conditions of regular long-haul or ultra-long range flights which use planned rest periods, can rely on augmented pilots having ample time to wake up, and always have two pilots in the cockpit. The available scientific data on the effects of current long-haul operations on fatigue and alertness can therefore not be translated to minimum crew operations yet, because especially the expected level of fatigue of the pilot flying (e.g. during less favourable times of day) should be further investigated first. In addition, the available data of regular long-haul operations do not allow to draw conclusions about effects of monotony and boredom, in-flight sleep and sleep inertia, and circadian factors on fatigue and alertness levels during different reduced crew circumstances (e.g. duty length, time of day, level of fatigue at start of duty etc). Other factors to be addressed are the (assessment of the) cognitive performance of the pilot resting when resuming duty, and potential effective mitigation strategies targeting either the individual pilot or the cockpit environment.

Based on the existing scientific literature, it remains unknown what the most optimal rest/wake ratio for reduced crew operations would be. Next to the research topics addressed above, future studies should incorporate multiple realistic rest/wake ratio scenarios in (simulated) reduced crew operation, implementing the proposed rest period of 2.5 hours, and taking into account the specific eMCO related factors (e.g. noise of PF engaged in flying tasks, timing, personal characteristics). By doing so, reliable results regarding sleep quality and length in the proposed cockpit seats would be acquired, and assumptions could be made about the fatigue levels (and thus levels of safety) during eMCO scenarios using the current FTL rules. Although OEMS have indicated that the benefits related to eMCO in-flight rest opportunities could potentially lead to extension of these rules, there is currently no data available to substantiate these assumptions.

# 7. References


**General**

Åkerstedt T. (1998). Shift work and disturbed sleep/wakefulness. Sleep Medicine Reviews, 2(2):117–28.

Bourgeois-Bougrine, S., Carbon, P., Gounelle, C., Mollard, R., and Coblentz, A. (2003). Perceived fatigue for short- and long-haul flights: a survey of 739 airline pilots. Aviat. Space Environ. Med. 74, 1072–1077.

Caldwell JA, & Gilreath SR. (2002). A survey of aircrew fatigue in a sample of U.S. Army aviation personnel. Aviation, Space and Environmental Medicine, 73:472–480

Caldwell JA, Mallis MM, Caldwell JL, et al. (2009) Fatigue countermeasures in aviation. Aviat Space Environ Med 80: 29–59.

Dinges DF, Pack F, Williams K, et al. (1997). Cumulative sleepiness, mood disturbance, and psychomotor vigilance performance decrements during a week of sleep restricted to 4–5 hours per night. Sleep, 20(4):267–7.

van Drongelen, A., Boot, C. R., Hlobil, H., Smid, T., & van der Beek, A. J. (2017). Risk factors for fatigue among airline pilots. International archives of occupational and environmental health, 90, 39-47.

Folkard S, Åkerstedt T. A three-process model of the regulation of alertness-sleepiness. In: Broughton RJ, Ogilvie RD, editors. Sleep, Arousal, and Performance. Boston: Birkhäuser; 1992:11–26.

Folkard S, Tucker P. Shift work, safety and productivity. (2003). Occup Med (Lond). 2003 Mar;53(2):95-101.

Gander, P. H., Mulrine, H. M., van den Berg, M. J., Smith, A. A. T., Signal, T. L., Wu, L. J., & Belenky, G. (2014). Pilot fatigue: Relationships with departure and arrival times, flight duration, and direction. Aviation, Space, and Environmental Medicine, 85(8), 833–840.

Gardiner, C., Weakley, J., Burke, L. M., Roach, G. D., Sargent, C., Maniar, N., ... & Halson, S. L. (2023). The effect of caffeine on subsequent sleep: A systematic review and meta-analysis. Sleep Medicine Reviews, 101764.

Hall, S. J., Ferguson, S. A., Turner, A. I., Robertson, S. J., Vincent, G. E., & Aisbett, B. (2017). The effect of working on-call on stress physiology and sleep: A systematic review. Sleep medicine reviews, 33, 79-87.

Hilditch CJ, McHill AW. Sleep inertia: current insights. Nat Sci Sleep. 2019 Aug 22;11:155-165. doi: 10.2147/NSS.S188911. PMID: 31692489; PMCID: PMC6710480.

Jewett ME, Wyatt JK, Ritz-De Cecco A, Khalsa SB, Dijk D-J, Czeisler CA. Time course of sleep inertia dissipation in human performance and alertness. J Sleep Res. 1999;8(1):1–8.

Petrie KJ, & Dawson AG. (1997). Symptoms of fatigue and coping strategies in international pilots. International Journal of Aviation Psychology 7:251–258.

Petrilli RM, Roach GD, Dawson D, & Lamond N. (2006). The sleep, subjective fatigue, and sustained attention of commercial airline pilots during an international pattern. Chronobiology International, 23(6):1357–62.

Powell DM, Spencer MB, Holland D, Broadbent E, & Petrie KJ. (2007). Pilot fatigue in short-haul operations: effects of number of sectors, duty length and time of day. Aviation, Space, and Environmental Medicine, 78:698–701.

Rosekind, M. R., Gregory, K. B., Co, E. L., Miller, D. L., & Dinges, D. F. (2000). Crew factors in flight operations XII: A survey of sleep quantity and quality in on-board crew rest facilities (No. IH-013).

Saksvik, I. B., Bjorvatn, B., Hetland, H., Sandal, G. M., & Pallesen, S. (2011). Individual differences in tolerance to shift work–a systematic review. Sleep Medicine Reviews, 15(4), 221-235.

Torsvall L, Åkerstedt T, Gillander K, and Knuttson A. (1989). Sleep on the night shift: 24-hour EEG monitoring of spontaneous sleep/wake behaviour. Psychophysiology, 26(3):352-358,1989.

Vejvoda M, Elmenhorst EM, Pennig S, Plath G, Maass H, et al. Significance of time awake for predicting pilots´ fatigue on short-haul flights: implications for flight duty time regulations. J Sleep Res. 2014; 23(5):564–567.

Wingelaar-Jagt YQ, Wingelaar TT, de Vrijer L, Riedel WJ, Ramaekers JG. Daily caffeine intake and the effect of caffeine on pilots' performance after extended wakefulness. Aerosp Med Hum Perform. 2023; 94(10):750-760.

**Peer-reviewed selection**

Cabon, P. H., Coblentz, A., Mollard, R., & Fouillot, J. P. (1993). Human vigilance in railway and long-haul flight operation. Ergonomics, 36(9), 1019-1033.

Coombes, C., Whale, A., Hunter, R., & Christie, N. (2020). Sleepiness on the flight deck: Reported rates of occurrence and predicted fatigue risk exposure associated with UK airline pilot work schedules. Safety science, 129, 104833.

Gander, P., Mulrine, H. M., van den Berg, M. J., Wu, L., Smith, A., Signal, L., & Mangie, J. (2016). Does the circadian clock drift when pilots fly multiple transpacific flights with 1-to 2-day layovers?. Chronobiology international, 33(8), 982-994.

Gregory, K. B., Soriano-Smith, R. N., Lamp, A., Hilditch, C. J., Rempe, M. J., Flynn-Evans, E. E., & Belenky, G. L. (2021). Flight crew alertness and sleep relative to timing of in-flight rest periods in long-haul flights. Aerospace Medicine and Human Performance, 92(2), 83-91.

Hilditch, C. J., Arsintescu, L., Gregory, K. B., & Flynn-Evans, E. E. (2020). Mitigating fatigue on the flight deck: how is controlled rest used in practice?. Chronobiology International, 37(9-10), 1483-1491.

Holmes, A., Al-Bayat, S., Hilditch, C., & Bourgeois-Bougrine, S. (2012). Sleep and sleepiness during an ultra long-range flight operation between the Middle East and United States. Accident Analysis & Prevention, 45, 27-31.

Honn, K. A., Satterfield, B. C., McCauley, P., Caldwell, J. L., & Van Dongen, H. P. (2016). Fatiguing effect of multiple take-offs and landings in regional airline operations. Accident Analysis & Prevention, 86, 199-208.

Powell, D., Spencer, M. B., & Petrie, K. J. (2011). Automated collection of fatigue ratings at the top of descent: a practical commercial airline tool. Aviation, Space, and Environmental Medicine, 82(11), 1037-1041.

Powell, D., Spencer, M. B., Holland, D., & Petrie, K. J. (2008). Fatigue in two-pilot operations: implications for flight and duty time limitations. Aviation, space, and environmental medicine, 79(11), 1047-1050.

Rempe, M. J., Basiarz, E., Rasmussen, I., Belenky, G., & Lamp, A. (2022). Pilot In-Flight Sleep During Long-Range and Ultra-Long Range Commercial Airline Flights. Aerospace Medicine and Human Performance, 93(4), 368-375.

Roach, G. D., Darwent, D., & Dawson, D. (2010). How well do pilots sleep during long-haul flights?. Ergonomics, 53(9), 1072-1075.

Roach, G. D., Darwent, D., Sletten, T. L., & Dawson, D. (2011). Long-haul pilots use in-flight napping as a countermeasure to fatigue. Applied ergonomics, 42(2), 214-218.

Roach, G. D., Matthews, R., Naweed, A., Kontou, T. G., & Sargent, C. (2018). Flat-out napping: The quantity and quality of sleep obtained in a seat during the daytime increase as the angle of recline of the seat increases. Chronobiology international, 35(6), 872-883.

Roach, G. D., Petrilli, R. M., Dawson, D., & Lamond, N. (2012). Impact of layover length on sleep, subjective fatigue levels, and sustained attention of long-haul airline pilots. Chronobiology international, 29(5), 580-586.

Russo, M. B., Kendall, A. P., Johnson, D. E., Sing, H. C., Thorne, D. R., Escolas, S. M., ... & Redmond, D. P. (2005). Visual perception, psychomotor performance, and complex motor performance during an overnight air refueling simulated flight. Aviation, space, and environmental medicine, 76(7), C92-C103.

Sallinen, M., Åkerstedt, T., Härmä, M., Henelius, A., Ketola, K., Leinikka, M., ... & Puttonen, S. (2018). Recurrent on-duty sleepiness and alertness management strategies in long-haul airline pilots. Aerospace medicine and human performance, 89(7), 601-608.

Sallinen, M., Onninen, J., Ketola, K., Puttonen, S., Tuori, A., Virkkala, J., & Åkerstedt, T. (2021). Self-reported reasons for on-duty sleepiness among commercial airline pilots. Chronobiology International, 38(9), 1308-1318.

Sallinen, M., Sihvola, M., Puttonen, S., Ketola, K., Tuori, A., Härmä, M., ... & Åkerstedt, T. (2017). Sleep, alertness and alertness management among commercial airline pilots on short-haul and long-haul flights. Accident Analysis & Prevention, 98, 320-329.

Sallinen, M., van Dijk, H., Aeschbach, D., Maij, A., & Åkerstedt, T. (2020). A large-scale European Union study of aircrew fatigue during long night and disruptive duties. Aerospace medicine and human performance, 91(8), 628-635.

Samel, A., Wegmann, H. M., Vejvoda, M., Drescher, J., Gundel, A., Manzey, D., & Wenzel, J. (1997b). Two-crew operations: stress and fatigue during long-haul night flights. Aviation, space, and environmental medicine, 68(8), 679-687.

Samel, A., Wegmann, H. M., & Vejvoda, M. (1997b). Aircrew fatigue in long-haul operations. Accident Analysis & Prevention, 29(4), 439-452.

Seah, B. Z. Q., Gan, W. H., Wong, S. H., Lim, M. A., Goh, P. H., Singh, J., & Koh, D. S. Q. (2021). Proposed data-driven approach for occupational risk management of aircrew fatigue. Safety and health at work, 12(4), 462-470.

Signal, T. L., Gander, P. H., van den Berg, M. J., & Graeber, R. C. (2013). In-flight sleep of flight crew during a 7-hour rest break: implications for research and flight safety. Sleep, 36(1), 109-115.

Wright, N., & McGown, A. (2001). Vigilance on the civil flight deck: incidence of sleepiness and sleep during long-haul flights and associated changes in physiological parameters. Ergonomics, 44(1), 82-106.

Wu, L. J., Gander, P. H., van den Berg, M., & Signal, T. L. (2018). Equivalence testing as a tool for fatigue risk management in aviation. Aerospace medicine and human performance, 89(4), 383-388.

Zaslona, J. L., O'Keeffe, K. M., Signal, T. L., & Gander, P. H. (2018). Shared responsibility for managing fatigue: Hearing the pilots. PLoS One, 13(5), e0195530.

**Grey literature selection**

Airbus (2004). Getting to grips with Fatigue & Alertness Management. Report STL 945.2796/04. Issue 3. Flight Operations Support & Line Assistance-Customer Services. Airbus, 31707 BLAGNAC Cedex FRANCE. https://www.smartcockpit.com/docs/Getting_To_Grips_With_Fatigue_and_Alertness_Management.pdf (accessed 2 November, 2023)

Bhana H (2009). "Correlating Boredom Proneness With Automation Complacency in Modern Airline Pilots" (2009). Theses and Dissertations. 371. https://commons.und.edu/theses/371

CAA-UK (2003). Civil Aviation Authority, "A Review of In-flight Napping Strategies" CAA Paper 2003/8, 1 Sept 2003. www.caa.co.uk

CAA (2005). Aircrew Fatigue: A Review of Research Undertaken on Behalf of the UK Civil Aviation Authority. Paper 2005/04. https://publicapps.caa.co.uk/docs/33/CAAPaper2005_04.pdf (accessed 2 November 2023).

Co EL, Gregory KB, Johnson JM, & Rosekind MR (1999). Crew factors in flight operations XI: a survey of fatigue factors in regional airline operations. Report no NASA/TM-1999–208799. Moffett Field, CA: NASA-AMES Research Center.

EASA EBAA (2014). Stone & Spencer. EBAA/ECA Study of Fatigue in Air Taxi, Emergency Medical Service Commercial Air Operations. Presentation to EASA, Cologne, 27th October 2015. https://www.easa.europa.eu/en/downloads/43767/en (accessed 01 November 2023).

Evans J, Richards JR, Battisti AS. Caffeine. [Updated 2023 Jun 8]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2023 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK519490/

Greenblatt K, Adams N. Modafinil. [Updated 2023 Feb 6]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2023 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK531476/

ICAO (2011). Fatigue Risk Management System (FRMS) – Implementation guide for operators. https://www.icao.int/safety/fatiguemanagement/frms%20tools/frms%20implementation%20guide%20for%20operators%20july%202011.pdf (accessed 30 September 2023).

Klopping WAA, Jonkman AG, Valk PJ, Simons M. (2005) Efficacy of modafinil and caffeine to counteract hypnotic induced sleepiness during sustained operations. Neuilly-sur-Seine, France: RTO.

Rosekind MR, Graeber RC, Dinges DF, Connell LJ, Rountree M, & Gillen KA. (1994). Crew factors in flight operations: IX. Effects of a planned cockpit rest on crew performance and alertness in long-haul operations.

NASA Technical Memorandum 103884.Moffett Field, CA: NASA Ames Research Center.

Simons M, Valk PJL, & de Ree JJD, Veldhuijzen van Zanten OBA, D'Huyvetter K. (1994). Quantity and quality of onboard and layover sleep: effects on crew performance and alertness. Report RD-31-94. Soesterberg: Netherlands Aerospace Medical Centre.

Simons M, Valk PJL (1997). Effects of a Controlled Rest on the Flight Deck on Crew Performance and Alertness. Report: NLRGC 1997-B3. Netherlands Aerospace Medical Centre, Soesterberg, Netherlands.

Simons M, Spencer MB (2007). Extension of flying duty period by in-flight relief. TNO report TNO-DV 2007 C362. TNO Defence, Security and Safety. Soesterberg, Netherlands.

Simons R. (2017). Assessment for fatigue among pilots (Chapter 10). In: R. Bor, C. Eriksen, M. Oakes, P. Scragg (Eds) Pilot Mental Health Screening and Assessment: A Practitioners Guide. Routledge - Taylor & Francis Group, Abingdon, UK. December 2017. p.172-202.

Spencer MB, Wilson AL, & Bunting AJ.(1998) The CHS Alertness Model and the prediction of performance. DERA Report No DERA/CHS/PPD/CR980191. Farnborough: DERA.

Spencer MB, Robertson KA. (1999). The Haj operation: alertness of aircrew on return flight between Indonesia and Saudi Arabia. DERA Report No. DERA/CHS/PPD/CR980207/1.0, Farnborough: DERA.

Spencer MB. (2002). Modelling of aircrew alertness in future ultra long-range schedules, based on a city pair. QinetiQ Report No. QINETIQ/CHS/P&D/CR020047/1.1, 2002.

Spencer MB, Robertson KA. (2004). Aircrew alertness on the Singapore–Los Angeles route: final report. QinetiQ Report No. QINETIQ/KI/CHS/CR050022/1.0, Farnborough: QinetiQ.

Valk PJL, & Simons M. (1998). Pros and cons of strategic napping on long haul flights. AGARD-CP-599 (pp. 5–1/5–5), Neuilly-sur-Seine: NATO-AGARD.

Valk P.J.L.; Simons M.; Goei J.H. & van Hijum S.M. (2003), Evaluation of the Fit-to-Fly Checklist on Long Haul and Short Haul Flights, Proceedings 15 th EASS – FSF & ERA Conference 'Change: A safety Challenge', March 2003, Geneva, Switzerland. Flight Safety Foundation, Alexandria, Virginia USA. pp.9-16.

European Union Aviation Safety Agency

European Union Aviation Safety Agency

Konrad-Adenauer-Ufer 3
50668 Cologne
Germany

Mail EASA.research@easa.europa.eu
Web www.easa.europa.eu

**An Agency of the European Union**