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D-5 REPORT ON PILOT INCAPACITATION MANAGEMENT

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

An Agency of the European Union

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SUMMARY

This report describes types of incapacitation and possible methods for incapacitation detection specifically in the context of Extended Minimum Crew Operations (eMCO) although also seen relevant for know-how development of Single Pilot Operations (SiPO). The report discusses approaches to enable safe flight in case of pilot incapacitation. Results of a survey among pilots on flight crew incapacitation are presented, and aspects relevant for certification are described.

Problem area

Incapacitation of the pilot-flying is one of the main hazards that must be mitigated to enable eMCO. This requires timely detection of incapacitation and provisions to keep the aircraft in a safe state until the pilot resting is able to operate the aircraft.

Description of work

The work describes results of a literature analysis and a survey sent out amongst the pilot community.

Application

This report is relevant for the safety assessment of the eMCOs. However, the technology of pilot monitoring is also applicable for safety assessment of SiPOs.

CONTENTS

ABBREVIATIONS

ACRONYM	DESCRIPTION
A/C	Aircraft
AED	Automated External Defibrillator
AFM	Aircraft Flight Manual
ATC	Air Traffic Control
ATPL	Airline Transport Pilot License
BIS	Bispectral Index
CAT	Commercial Air Transport
CBA	Cost Benefit Analysis
CDU	Control Display Unit
CFIT	Controlled Flight Into Terrain
CS	Certification Specifications
CVD	Cardiovascular Disease
DLR	German Aerospace Centre
DLR FT	DLR Institute of Flight Systems
EASA	European Union Aviation Safety Agency
ECAM	Electronic Centralised Aircraft Monitor
EFIS	Electronic Flight Instrument System
EICAS	Engine Indicating and Crew Alerting System
eMCO	Extended Minimum Crew Operations
EPAM	Electronic Pilot Activity Monitor
FC	Flight Crew
FMS	Flight Management System
GCAS	Ground Collision Avoidance System
GDPR	General Data Protection Regulation
HF	Human Factors
HMI	Human Machine Interface
ICAO	International Civil Aviation Organization
LED	Light Emitting Diode
MTOM	Maximum Takeoff Mass
MCP	Mode Control Panel
NLR	Royal Netherlands Aerospace Centre
PF	Pilot Flying
PR	Pilot Resting
OCC	Operations Control Center
OEM	Original Equipment Manufacturer
OM	Operations Manual
RA	Resolution Advisory

RMP	Radio Management Panel
TAWS	Terrain Awareness and Warning System
TCAS	Traffic Collision Avoidance System
VCS	Vigilance Control System

1. Context

1.1 Background

Due to the ongoing developments in technology, automation and autonomous unmanned aircraft, 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 is considered from both the safety as well as efficiency perspectives.

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 where, during the cruise flight phase only, one pilot is allowed at the controls; however, offering 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 Regulation.
- 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 an overall level of safety equivalent to today's two-pilot operations.

The main challenges when moving from conventional multi-crew operations to eMCO, and also to SiPO, includes ensuring adequate detection of pilot incapacitation and ensuring risk mitigation in case of incapacitation, including mental health issues (EASA 2023).

1.2 Scope of the document

This document specifically provides an evaluation of pilot incapacitation in the context of eMCO although it could be setting an information and knowledge base for SiPO as well. In case the pilot flying becomes incapacitated during an eMCO segment, on-board systems must make certain that flight safety is being maintained. This means that on-board systems must detect incapacitation of the pilot flying, the pilot resting must be alerted and the aircraft must be maintained in a safety state until the pilot resting is able to take control.

This document provides an overview of types of incapacitation and technologies that are available to detect these types of incapacitation. Possible solutions to maintain flight safety during eMCO when one pilot becomes incapacitated are compared with the reference situation of today's two-pilot operations. Results of a survey among European pilots on topics including (subtle)incapacitation and fatigue are presented and interpreted. The document also describes the potential impact of pilot incapacitation and incapacitation detection on certification requirements.

1.3 Methods

This document is based on information from scientific literature and an on-line survey.

1.3.1 Literature review

The two different approaches used for literature research are described below.

1.3.1.1 Literature review on pilot incapacitation and pilot monitoring

Initially, a variety of relevant search terms were added in GoogleScholar, such as 'Single Pilot Operations" and "pilot incapacitation", depending on the topic of interest. Resulting results were assessed one by one, after which relevant results were saved for reading and later reference. This approach was followed to get a broad overview of the available literature and to know where information could potentially be lacking. Next, a more systematic search was conducted by adding a number of search terms and criteria as summarised in Table 1-1.

Table 1-1: Literature review search criteria for pilot incapacitation and pilot monitoring

Relationship	Suggestions	Languages	Period
Single pilot operations; pilot monitoring; human performance; commercial aviation; medical; cognitive science; physiology	Pilot incapacitation; [Flight crew, Cockpit, Aviation]; physiological measurements (real-time); Cognitive assessment (real-time)	English, Dutch, German, French, Swedish	From 2010 onwards

The resulting abstracts were then assessed by the researchers.

1.3.1.2 Literature review on safe autoflight in case of incapacitation

A brainstorming for related search terms and combinations of these was performed. Combinations of search terms were used to increase the number of relevant results while at the same time reducing unwanted results. As not all search engines were capable of searching wildcard strings like for example *"auto*flight"* the search had to be repeated until all combinations were covered, i.e. in this example "auto flight", "autoflight", "automatic flight" and "autonomous flight". Searches were performed on Google Scholar, Scopus, and ResearchGate for the time frame of the last 10 years. Depending on the search term, this yielded few to many results. The lists of results were then exported from the search engines and imported in the reference management and knowledge organization software Citavi, where the further analysis was carried out.

Further steps were the removal of search doublets (e.g., where sources have been found by more than one search engine), followed by a first rough reduction of clearly irrelevant search results based on the references' title. In a following screening step, the relevancy of the remaining references were pre-rated on a five star scale based on their abstract. In the last step of the screening process the list of pre-rated references was filtered to return only these with at least 3 of 5 stars. The full text of the remaining references were then analysed and applicable content was saved in so-called *knowledge items* and these were assigned to the overall topic of interest in Citavi. At the end of the process, this report was generated based on the extracted Citavi knowledge items.

1.3.2 Survey

An on-line survey was distributed across different European pilot organisations, including airlines and pilot unions, using the LimeSurvey platform.

The survey (Appendix A) included 31 questions across seven topical groups, including (subtle) incapacitation, fatigue and sleep inertia. Other groups are informed consent, demographics and practical questions.

The survey was opened on 20 November 2023 and subsequently closed on 18 December 2023, allowing 6645 full responses. Additionally, there were 4646 respondents that started answering question but stopped well before reaching the final question. These incomplete responses were filtered out before downloading the responses.

Further data processing steps involve filtering out unrealistic values, nonsense responses, or responses that do not meet the criteria set in the question. The data processing steps are shown in Figure 1.1.

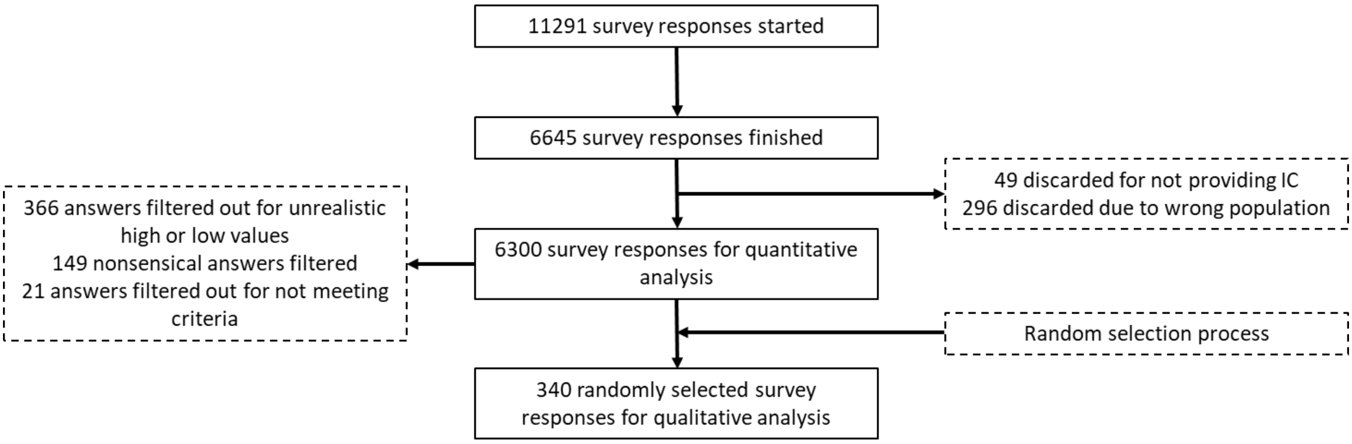

Figure 1.1. Data processing of survey results

In some cases individual questions were skipped by survey respondents. These cases were not treated as an incomplete response but were included in the 6300 survey responses for quantitative analysis.

2. Types of incapacitation

2.1 Types and frequency of incapacitation

According to the definition of ICAO (ICAO, 2012), incapacitation means any reduction in medical fitness to a degree or of a nature that is likely to jeopardize flight safety. For aircrew, this generally means that the incapacitation occurs in-flight.

Incapacitation can be described as a phenomenon that is distributed over two axes as shown in Figure 2.1. One axis represents total versus partial incapacitation. The other axis represents subtle versus obvious incapacitation.

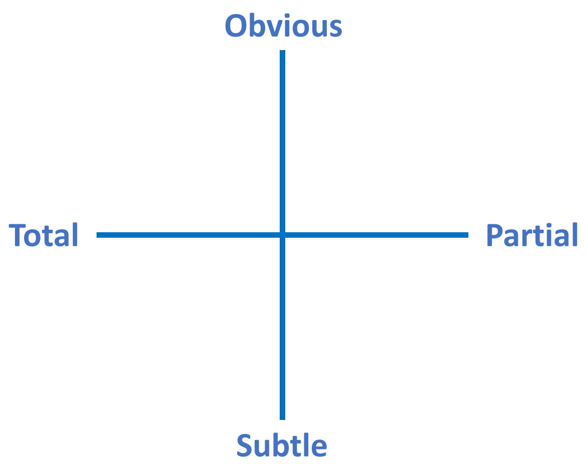

Figure 2.1. Incapacitation visualised over two axes.

Total (100%) incapacitation (e.g., sudden death, acute coronary syndrome, epileptic seizure, panic attack, psychosis) means that the pilot is not capable of performing any task. Partial incapacitation is a condition where the pilot is still capable of performing some tasks, but is not fully capable of properly performing all the tasks that are required for safe and efficient flight. Some sources use the term impairment: a partial incapacitation associated with symptoms that resulted, or would have had the propensity to result, in a reduction of function or distraction from the flight crew task, but would be unlikely to have caused loss of control of an aircraft (Evans & Radcliffe 2012). In cases of partial incapacitation pilots may be able to self-declare the incapacitation.

Subtle incapacitation is defined by ICAO (2012) as a mild, sometimes difficult discernible reduced state of alertness, a mental preoccupation which may result in a lack of appreciation of significant factors, increased reaction time, and impaired judgement. Subtle incapacitations can be caused by mental or physiological conditions which both can lead to distractions of flight tasks. A physiological condition that can lead to subtle incapacitation is hypoxia. Many mental conditions or states can cause subtle incapacitation, such as mild depression, fatigue, or preoccupation with thoughts of unresolved or towering personal issues. A particular category of subtle incapacitations has been identified as "cognitive." The problem created by these incapacitations is how to deal with a pilot who is "mentally disoriented, mentally incapacitated or obstinate, while physically able and vocally responsive" (ICAO, 2012).

Incapacitation can be progressive, developing from partial to total incapacitation. Suddenness of incapacitation is the rapidity at which the incapacitation develops. Sudden incapacitation is a significant reduction in medical fitness jeopardizing flight safety which occurs suddenly without heralding signs or symptom. Examples are sudden death, syncope, stroke and epileptic seizure. Gradual incapacitation is a reduction in medical fitness that is announced by symptoms such as headache, nausea, fatigue, chest pain, respiratory difficulties. In cases of gradual incapacitation pilots may be able to self-declare the incapacitation/impairment.

Causes of incapacitation or impairment can be medical conditions or external. Examples of external causes of incapacitation are hypoxia and fume intoxication. Pilots have to pass regular medical examinations in order to maintain their licence, but in-flight medical incapacitation can still occur if a medical condition is not detected during the examination or if the condition develops after the examination. Table 2-1 gives an overview of possible types of medical incapacitation and impairment (Simons et al, 2019; Hageman et al; Laval-Meunier et al 2013, Evans & Radcliffe 2012):

Table 2-1: Possible types of medical incapacitation and impairment

Sudden death (fatal arrhythmias, acute myocardial infarction, intracranial haemorrhage/massive stroke, massive pulmonary embolism, and acute aortic rupture from aneurysm or dissection)
Cardiovascular diseases
Stroke (cerebral ischemic infarction, cerebrovascular accident, cerebral haemorrhage)
Syncope / Loss of consciousness (neurocardiogenic or vasovagal syncope, orthostatic hypotension, carotid sinus hypersensitivity, neurological, endocrinological, and psychiatric disorders)
Epileptic seizure
Migraine
Acute psychosis
Major depressive disorder
Panic attack
Nephrolitiasis
Gastro-interitis
Otorhinolaryngological diseases (ear, nose and throat)
Ophthalmic diseases
Barodontalgia
Infectious disease
Musculoskeletal disease
Hyperventilation
Spontaneous abortion
Hypoxia
Intoxication (drugs, alcohol)
Aerotoxic syndrome

Although ICAO defines incapacitation as a form of reduction in medical fitness, fatigue can also be considered as a form of incapacitation. The survey responses indeed indicate that pilots do not strictly use the ICAO definition when referring to ‘incapacitation’ and refer to any form of reduced fitness, whether from medical causes or as a result of fatigue, as incapacitation or impairment. ICAO defines fatigue as physiological state of reduced mental or physical performance capability resulting from sleep loss or extended wakefulness, circadian phase, or workload (mental and/or physical activity) that can impair a crew member’s alertness and ability to safely operate an aircraft or perform safety-related duties. Similarly sleep inertia may be seen as a form of incapacitation. ICAO defines sleep inertia as transient disorientation, grogginess and performance impairment that can occur after wakening. A pilot that falls asleep due to excessive fatigue can be considered to be fully incapacitated.

2.2 Frequency of incapacitation

Evaluating literature on the frequency of inflight incapacitations is hindered by the fact that a comparison of the results of studies is complicated by inconsistency in the denominator, e.g., '10^6 flight hours', 'number of pilots studied', 'year', 'fatal accidents' and non-uniformity of the definition of incapacitation: it might be 'any change in ability to function appropriately', 'a medical event that resulted, or would have had the propensity to result, in an inability to act as flight crew for at least 10 min' (Evans & Radcliffe, 2012), or a partial incapacitation associated with symptoms that (would have) resulted in a reduction of function or distraction from the flight crew task. Moreover, it might be only in-flight or both in- and off-duty, it can be any incapacitation or only (e.g.) cardiac incapacitation, and it might be caused by either a disease or by external causes (e.g., fume intoxication or hypoxia) (Simons et al, 2019).

In-flight incapacitation as a consequence of medical problems is a rare event occurring up to 0.45 times per 10^6 flight hours (DeJohn et al 2004). There are no reliable data on partial incapacitation because it is not systematically reported.

According to a worldwide survey among commercial air transport pilots that was carried out in 1991 (James & Green 1991), the most frequent causes of incapacitation were gastrointestinal (58.4%), earache due to a blocked ear (13.9%), and faintness or general weakness (8.5%). The most common phases of flight where incapacitations occurred were enroute (42.1%), followed by climb (18.4%), descent (17.3%), and on the ramp (11.4%). Safety-of-flight was felt to be potentially affected in 45% of cases and definitely affected in 3% of cases. Of those reporting that safety-of-flight had been affected, 43% stated the incapacitation event placed the remaining aircrew under maximum workload.

Similarly, other studies looked at in-flight incapacitation rates with various participant groups (DeJohn et al., 2006). This review article reports that overall, the main medical events affecting pilots were found to be myocardial infarctions, cardiac arrythmias and epileptic seizures, yet data stems from multiple sources that are broader than simply in-flight medical events. When looking at pilots whose careers had been ended due to medical events in the UK for example, about half of pilots had psychiatric problems, while the other half struggled with cardiovascular or respiratory problems, or diabetes.

There is an increased risk of pilot incapacitation with age (Evans & Radcliffe 2012), but not all causes of medical incapacitation are age related. Fifty to seventy percent of the medical incapacitations are caused by problems such as acute gastroenteritis, headache, and ear/sinus conditions which are not age-related. The medical conditions that are age dependent are caused by cardiovascular, neurological, or psychiatric conditions. These include sudden death, coronary artery disease, cardiac arrhythmias, pulmonary embolism, stroke (cerebral ischemic infarction, cerebrovascular accident, cerebral haemorrhage), syncope, late-onset seizure(s), and acute psychosis and can result in sudden and complete incapacitation (Simons et al 2019). In an attempt to estimate incapacitation rates as a function of pilot age, Simons et at (2019) used the general population mortality rate for all cardiovascular conditions as a lower estimate, and the general population hospital admission rate as an upper estimate for sudden and complete incapacitation. A reduction factor was applied based on the literature data concerning the Standardized Mortality Ratio of commercial air transport pilots compared to the general population mortality.

The calculated lower and upper estimates of the probability per hour of sudden and complete pilot incapacitation as presented in Table 2-2.

Table 2-2: Estimated probability per hour of sudden and complete pilot incapacitation as a function of age

Age category	Pilot incapacitation probability per hour - lower estimate-	Pilot incapacitation probability per hour - upper estimate-
25-34	$1.14x10^{-9}$	$5.94x10^{-8}$
35-44	$1.14x10^{-9}$	$5.94x10^{-8}$
45-54	$1.14x10^{-8}$	$5.22x10^{-7}$
55-64	$6.05x10^{-8}$	$1.04x10^{-6}$
65-74	$1.60x10^{-7}$	$1.63x10^{-6}$

2.3 Prevention and medical screening

Of in-flight incapacitations, 50 to 70% are caused by problems that cannot be predicted during the periodical medical screening and are barely preventable: acute gastroenteritis (diarrhoea, vomiting), headache, and barotrauma/ear/sinus conditions (ICAO, 2012; James & Green, 1991). The remaining 30–50% of total in-flight incapacitations includes causes such as sudden cardiac death, acute coronary syndrome, cardiac arrhythmias, pulmonary embolism, stroke, epileptic seizures, and panic attacks (Evans & Radcliffe, 2012; Simons et al., 2019).

The largest number of total incapacitations is attributed to cardiovascular diseases, and it is therefore considered that prevention of cardiovascular events may offer the best opportunity to significantly reduce the in-flight medical incapacitation risk. Although it is known that atherosclerosis already starts to develop in early adulthood, or even childhood (Hong, 2010) the symptoms and life-threatening manifestations of cardiovascular disease (CVD) start to emerge at middle age, especially in those over the age of 40, which is demonstrated by an at least 3- fold increase of all cardiovascular diseases (CVD) and myocardial infarction mortality in those over 40 years (AHA, 2018) and a 5-fold increase of new stroke cases in the 45-54 age group as compared with the under 45 age groups (Finegold et al., 2013; Buddeke et al., 2017). In addition, known cardiovascular risk factors are hypertension, obesity, diabetes mellitus, hypercholesterolemia, positive family history, gender, and smoking. The cardiovascular burden is given by the severity and amount of these cardiovascular risk factors.

Based on this reasoning and in agreement with the recommendation of the NATO HFM-251 Occupational Cardiology in Military Aircrew working group (Gray et al., 2019) it is assumed that a thorough CVD risk assessment in CAT pilots, especially from the age of 40 onwards, will further reduce the risk of total in-flight incapacitation and will at the same time contribute to individual prevention of CVD.

It is assumed that partial incapacitation is more frequent than total incapacitation, but there are no data to support this assumption because partial incapacitation is not systematically reported.

Prevention of incapacitation is important to minimise incapacitation risk and this should include prevention of incapacitation due to psychological issues. The identification of psychological and cognitive problems should be an important aim of the aeromedical examination. However, at least 50% of the mental health problems of pilots will be missed at the aeromedical examination because pilots hide their mental problems due to fear of losing their license if mentioning or admitting to have mental health problems (Strand et al., 2022; Hoffman et al., 2023). Available mental health questionnaires are not useful to identify mental health problems in pilots because each pilot can easily recognise what the desired answers should be to please the aeromedical examiner. Mental causes of incapacitation include reduced alertness and executive functioning, depersonalization – derealization, panic attack, agitation, intrusive thoughts, compulsions, aggressive behaviour, hallucinations, delusions, and suicide.

3. Monitoring of the pilot and detection of incapacitation

It is clear that measurement of the pilot's psycho-physiological state and identification of adverse human physical and cognitive impairment will be critical technology for eMCO (Baily et al, 2017). Aircraft that are allowed to perform eMCO will have to be equipped with a pilot monitoring system that evaluates the pilot's state to support pilot self-assessment and ensure flight safety in case of pilot incapacitation or impairment. Such systems have already been and proposed in the literature (Liu et al, 2016). Several health monitoring systems are under development in the automotive sector (Harris, 2007). It is, however, still questionable whether such systems can reliably detect all possible contexts of incapacitation while implemented in a nonintrusive and comfortable way (Bilimoria et al, 2014).

It should be considered that European General Data Protection Regulation (GDPR) and national medical confidentiality laws prohibit the use of individual medical data unless it is in the framework of a medical treatment contract, or in a scientific study approved by a Medical Ethics Committee in which data will anonymously registered and informed consent of the study subjects is obtained. Therefore GDPR, national laws, and refusal of pilots may prevent any monitoring of vital signs by medical devices.

3.1 Monitoring and detection in multi-crew cockpits

In the current multi-crew cockpit, pilots are trained to monitor each other for signs of (subtle) incapacitation. Total incapacitation is considered a major failure condition that will be clearly noticed by the colleague pilot, who will take action according to the instructions of the incapacitation procedures as trained in the incapacitation training of each ATPL pilot. In a multi-pilot flight operation, the safety risk will be mitigated considerably because the colleague pilot takes over all tasks according to standard procedures. Subtle incapacitation can be detected by a colleague pilot who notices that the performance of the subtly incapacitated pilot is not appropriate. Therefore, ATPL pilots are trained to monitor their cockpit colleagues (Crew Resource Management, Two persons on Flight Deck, Two Communication Rule, Fail Safe Crew concept) and this forms an effective mitigation measure against subtle incapacitation. The "Two Communication Rule" states that "flight crew members should have a very high degree of suspicion of a subtle incapacitation whenever a flight crew member does not respond appropriately to two verbal communications, or whenever there is no appropriate response to any verbal communication, associated with a significant deviation from a standard flight profile." Pilots have to speak to their colleague if they notice irrational behaviour or inappropriate actions and, if necessary, take over the management of the flight. The safety risks of subtle incapacitation may be significant even in a multi-crew cockpit because a colleague may not be always immediately aware of the dysfunction of his/her colleague and/or finds it difficult to take over the tasks because the subtly incapacitated colleague might deny or be unaware of any dysfunction.

The effectivity of the two-person crew in preventing aircraft accidents due to pilot incapacitation is difficult to quantify because of a lack of data on the prevalence of in-flight incapacitation (total and partial). The sparsity of accidents involving pilot incapacitation suggest that the two-person crew is effective in preventing accidents due to incapacitation. Known incapacitation related accidents involve incapacitation of both pilots due to a common cause e.g. hypoxia, such as the Helios Airways accident in 2005 (AAIASB 2006) and cases of pilot suicide, such as the Germanwings accident in 2015 (BEA 2016).

A study of simulated subtle pilot incapacitation showed a range of time before detection of the pilot's condition of 30 seconds to 4 minutes, with an average of 1.5 minutes (Harper et al 1971).

3.2 Monitoring and detection in eMCO

3.2.1 Monitoring pilot vital signs

Solutions for pilot incapacitation events rely upon an accurate detection of the incapacitation in the first place (Faulhaber 2021). Real-time monitoring of pilots could incorporate measures that assume incapacitation is often a progressive state, and early symptoms might assist in identifying less than optimal conditions. Such monitoring also could be in the form of assessing the physical state and/or mental state of the pilot, with the latter being relatively more difficult to achieve (Johnson et al 2012).

Existing methods to monitor vital signs include electrocardiography, electro-encephalography, respiration rate, blood pressure, heart rate and heart rate variability, pulse wave or pulse oximetry, functional near-infrared spectroscopy and eye tracking. Electroencephalography (EEG) can be used to provide neural index of cognition. Electrocardiography (ECG) is frequently used to monitor the cardiac waveform and to detect cardiovascular issues. Functional Near-infrared spectroscopy (fNIRS) is a non-invasive technique for brain monitoring that can measure response to cognitive demands (Ferreri et al, 2014). Where electroencephalography (EEG) is based on measurement of electrical current in different areas of the brain, fNIRS focusses on oxygen saturation of the blood in different areas of the brain. Both provide information about activity in different regions of the brain. Respiration rate and pulse oximetry can be used for the detection of sudden death and hypoxia. The eye and visual system, under central nervous system control, can also provide information about an individual's cognitive state. Changes in ocular measures such as eye closure, eye movements and pupillary response occur as a function of the cognitive state (Caldwell et al., 2009). Facial expression assessment technology is currently being validated as a fatigue detection device (Sundelin et al 2013, Li et al 2020) and for the detection of certain types of medical incapacitation (Reston et al 2022). Sections 3.2.1.1 to 3.2.1.5 provide more detailed information about several existing bio-behavioural measures.

The usefulness of such technologies as real-time indicators of the physical state of the pilot is dependent on the requirements and conditions of the operational environment and some may not even be practical for use in highly restrictive environments such as the flight deck. Some techniques may have been successfully introduced in other domains, but while an automated, real-time technology may be valid in one operational environment, it does not always transition to another operational environment without the emergence of implementation obstacles (Caldwell et al., 2009). From the perspective of human acceptance these measurements should be comfortable and non-intrusive to wear and also not-intrusive in pilots' personal life, and therefore not record more data than strictly necessary.

Some of these techniques are used as support tool in some clinical settings to monitor intensive care patients or predict long-term (5-10 year) risks. Most sensor methods are used in experimental settings to study physiological variables instead of using them as a vital alarming tool. Widely known problems with such systems concern sensitivity, specificity, lack of predictive value, sensitivity for electromagnetic radiation, artefacts, and operational reliability. In general, high levels of sensitivity lead to a high number of false warnings, whereas warnings come too late if specificity is set at a high level. I.e. a pilot has to be sleeping (or dead) for several minutes before the algorithms can reliably mention that this pilot is sleeping (or dead). An example to measure the level of consciousness is bispectral index (BIS) monitoring, which is a bi-spectral analysis of the electro-encephalogram and involves the placement of electrodes on the patient's forehead. It is used to monitor the depth of anaesthesia to prevent intraoperative awareness of the patient in order to mitigate long-term psychological consequences. The algorithm is currently not designed to detect unconsciousness, but BIS might be used to develop an algorithm that detects any level of unconsciousness. Such development will need considerable time and testing before it might be used in eMCO. In this context, it should be considered that one of the flaws of the BIS method is interference from electromagnetic radiation which causes artefacts and impairs the ability of the BIS monitor to accurately assess the changes in the depth of anaesthesia.

There are many personal health monitoring systems on the market. Most of them lack reliability and sufficient specificity for clinical use. Many so-called smart watches measure a one-lead ECG signal that can indicate cardiac rhythm disturbances such as atrial fibrillation or ventricular tachycardia. In the medical profession such systems are sometimes referred to as “Smartwatch monsters” due to their sensitivity for electromagnetic and movement artefacts mimicking cardiac events (Russo et al., 2023). Automated interpretation of 12-lead ECGs is still not accurate enough for clinical use (Katoh et al., 2021).

Algorithms of the various tools might be improved by using artificial intelligence (AI), but systems should in that case be developed particularly aimed at predicting sudden in-flight incapacitation of pilots.

3.2.1.1 Heart rate (variability)

Heart rate (variability) is applied as an indicator of mental workload, stress and fatigue (Mulder, 2004, Tran 2009).

The measured data must be compared against a reference recording in order to make statements about changes in the state of the operator. This reference measure is generally a heart rate recording of approximately five minutes during which the operator sits still and can be made outside the cockpit prior to the flight, for instance when the pilot reports for duty.

Different kinds of sensors exist to record heart rate data. Examples are sensors worn on the chest and around the wrist. Infra-red video images of the face can also be used as indicators of the heart rate. Heart rate measurement by sensors mounted in the seats are also proposed for monitoring flight crew incapacitation (NOVAlert, 2024).

Electrodes on the chest are most accurate but are intrusive to apply and to wear. The signal may be disturbed by muscle movement in the vicinity of the sensors. Such movement may be caused by moving the torso in the seat, but also by talking. Wrist worn devices are less intrusive but also less accurate. The tightness of the band around the wrist needs to be just right, not too tight and also not too loose. Arm and hand movements may influence the recording. A video-based heart rate assessment is less physically intrusive because there is no sensor mounted on the subject, but the fact that a camera is constantly aimed at the face of the subject may also be interpreted as an intrusive situation. This type of measurement is also sensitive to disturbances. The pilot needs to be facing the camera for a good measurement and the ambient lighting conditions may affect the data quality.

Absence of a heart rate is a clear indication of incapacitation, but disturbances of the signal may result in false alerts. Differences in heart rate or in heart rate variability can be used as indicators of partial incapacitation, but these measurements seem to be sensitive to different kinds of biases. Therefore, in clinical settings heart rate measurements are often combined with other measures to improve the quality of the assessment.

3.2.1.2 Eye tracking

Eye tracking is often used as an indicator for mental- and/or visual workload, fatigue, attention, scanning randomness (versus being focussed) (Holmqvist, 2011), also in aviation (Peissel et al, 2018). Eye trackers are often video based and are either head-mounted or located at a fixed position facing the subject. Prior to the measurement the system must be calibrated, which may take several seconds to about an hour, depending on the type of equipment.

Head-mounted systems have the advantage that the eye is constantly monitored. Even when the pilot looks over the shoulder the eye scanning behaviour is being measured. The disadvantage is that there is always something on the head which might be uncomfortable or impractical. A fixed sensor facing the subject is less physically intrusive but the subject needs to look into the direction of a sensor in order to have a measurement. Multiple sensors are needed to track eye movements when the subjects move the head. Both head-mounted and fixed sensors may be influenced by changes in lighting conditions and by (sun)glasses worn by the subject. Also pilot-related factors such as droopy eyelids may influence the quality or robustness of the measurement.

Fatigue (eye closure) and the area of visual focus and attention can be applied as an indirect incapacitation indicator. Pupil dilation or -constriction can be indicative of changes in the subject's state linked to incapacitation. "Staring" might be applied as a precursor for fatigue or distraction.

3.2.1.3 Electro Dermal Activity (EDA)

Electro Dermal Activity (EDA), also called Galvanic Skin Response (GSR), is measurement of the electrical conductivity, or resistance, of the skin. This resistance is influenced by glands in the skin excreting several conductive substances. The activity of the glands is influenced by the autonomous nervous system, which in turn is influenced by the emotional state of a person. Therefore, changes in emotional state or arousal may be assessed via EDA. Mehler et al., 2009), Engström et al, 2005).

EDA is normally measured at those areas of the skin that have a higher of density of glands, such as hand palms or fingertips, but wrist worn devices and sensors located on the forehead are also used to measure EDA. To prevent interference with piloting tasks, wrist worn devices are probably most suitable.

A reference recording lasting several minutes is needed prior to starting the actual measurements.

3.2.1.4 Electroencephalography (EEG)

Electroencephalography (EEG) is the measurement of electrical activity of the brain. It provides information about the activity levels in different areas of the brain (Fang et al., 2020; Li et al., 2018, 2020; Nguyen et al., 2019). EEG uses sensors located around the skull. Depending on the location of the electrodes on the skull, information regarding activity of a particular area of the brain is measured.

A broad range of devices are available for such measurements. Often those (medical) devices have a great number (64 or even 256 or more) of electrodes that must be stuck to the head. To ensure conductivity most often gel is applied between the electrode and the skin. Installing and calibrating the equipment with many electrodes is time-consuming. Electromagnetic fields tend to interfere with such systems. In recent years more robust and simple EEG devices have become available, for instance medical quality devices with few electrodes, mounted in headphones with sensors that measure around the ear. Devices that measure EEG with very few electrodes on the forehead are also available. The frontal lobe of the brain (directly underneath the forehead) is responsible for a great deal of the processing of information and reasoning in the brain.

EEG is indicative of the brain activity of a human operator and can therefore be used to detect incapacitation. Differences between mental states, for instance being focussed and concentrated compared to dozing away or even sleeping, can be established with EEG. Also pilot mental workload can be measured by applying EEG (Wilson, 1994).

3.2.1.5 Functional Near Infra-Red Spectroscopy (fNIRS)

fNIRS uses infrared to measure oxygenation levels of blood in different areas of the brain. These oxygenation levels are indicative of brain activity. fNIRS is more robust and less influenced by biases than EEG, but also less sensitive to minor changes in brain activity. fNIRS is relatively slow since the hemodynamic response itself is rather slow (Gateau et al., 2015; Matsuyama et al., 2009). The calibration process is lengthy and complex.

Real time processing of fNIRS data is still a complex matter. Very few studies have successfully applied real time fNIRS data processing in the aviation domain.

3.2.1.6 Methodological triangulation

The measurements described above all have their advantages and disadvantages but there is not one single instrument that can be applied to measure all aspect of incapacitation.

3.2.2 Monitoring pilot activity

Pilot activity monitoring, i.e. monitoring inputs made by the pilot to aircraft systems, has also been proposed to make assessments of cognitive capability (Bilimoria et al 2014). Monitoring pilot activity for incoherent/nonsensical inputs or a lack of inputs could help determining whether the pilot is incapacitated.

Several pilot activity monitoring systems are already available for commercial aircraft. Boeing has developed a Crew Alertness Monitor (CAM) as a function of the Flight Management System that continuously monitors switch action on the Mode Control Panel (MCP), Electronic Flight Instrument System (EFIS), display select panel, Control Display Units (CDU), and radio transmitter microphone switches. When a predefined time elapses after the last switch action is detected, the Engine Indicating and Crew Alerting System (EICAS) alert message PILOT RESPONSE is displayed. The message is inhibited below 20,000 feet, during a climb, and when flaps are deployed.

A similar system was being developed for Airbus in the early 2000s. This Electronic Pilot Activity Monitor (EPAM) monitored crew interaction with the aircraft to detect excessive flight crew fatigue. It was based on the assumption that a pilot who is dozing off will interact less frequently with the aircraft. The device was connected to selected aircraft systems such as the FMS, Electronic Centralised Aircraft Monitor (ECAM), and the Radio Management Panel (RMP). When there is a lack of pilot interaction with any one of the multiple systems for a selected period a visual alert is provided. If another minute passes without activity, an auditory alarm is triggered. A study performed with 28 pilots on 28 flights, showed that just only considering the pilot input was not sufficient but the addition of, for example, eye movement measurement might be needed to reliably assess flight crew impairment due to fatigue (Cabon et al, 2003).

Garmin (Garmin, 2023) has developed an autoland function that can be activated by an absence of pilot interactions with the aircraft and avionics. Autoland allows aircraft flown by a single pilot to automatically divert and land at the nearest airport when the pilot is no longer capable of flying. It is available for G1000 NXi and G3000-equipped aircraft.

More sophistic pilot monitoring systems are described in literature but not yet practically implemented. Such systems would collect and analyse large amounts of data about the state of the aircraft, e.g. the flight path, the immediate environment around the aircraft, the weather and terrain information, and the pilot's input to control the aircraft. If the pilot's input does not match the proper reaction to the situation or the pilots are impaired, the machine learning system will first provide an advisory. When the situation becomes more urgent, this advisory will turn into a warning (Watkins et al, 2018). Note that this system was thought of in the context of a two-pilot cockpit.

Systems that monitor the operator's input are routinely applied in other modes of transport, particularly rail. Many trains and trams are equipped with so-called 'Dead Man's Switch' that needs to be regularly activated. Failure to activate the switch will first produce a warning signal. If there is still no action automatic braking is engaged. Reported problems with using a dead man's switch include musculoskeletal disorders caused by the repetitive operation of the switch (Foot and Doniol-Shaw, 2007) the possibility that the switch is activated despite incapacitation of the controller (particularly with foot pedals, as was the case in the Waterfall rail accident in Australia in 2003), and automatic behaviour of the operator which renders the system less effective (Oman and Liu, 2006).

Some car manufacturers have implemented systems that can monitor driver drowsiness and attention by monitor the steering pattern, the vehicle's position in the lanes, vehicle speed and input to the turn signal stalk but also head movements and eye blinking. These systems warn the driver to take a break when needed (Roadsafetyfacts, 2024). Some higher-end car manufacturers have implemented a system that that monitors driver behaviour by observing if the driver has not used the accelerator, brake, or steering wheel for a defined length of time; once a pre-set threshold of time has been exceeded the system will take control of the vehicle in order to bring it to a safe stop.

4. Enabling safe flight until resting pilot takes control

If the pilot flying (PF) becomes suddenly incapacitated during an eMCO segment the aircraft will be flying without pilot supervision. If the PF becomes incapacitated, the pilot resting (PR) must be called to the flight deck immediately. However, the PR's arrival may be delayed by several minutes due to factors as his or her sleep state, the distance between the flight crew rest area and the flight deck (when not collocated), or the availability of mobile life support systems in case of depressurization or smoke. Modern CAT aircraft systems to call relief crew consist of aural alert and a handset. Typically, the resting crew member is provided with information about the nature of the call over the handset after being awakened.

In the event of PF incapacitation during an eMCO segment, the flight deck may remain unoccupied for several minutes. Even if the pilot resuming has arrived on the flight deck, he or she will need time to overcome sleep inertia and get back in the loop before being able to take appropriate action.

4.1 Flight and flight path control

CAT aircraft typically fly with active autopilot and automatic thrust while following either an FMS flight plan or pilot-selected heading, speed, and altitude values as cleared by ATC. Pilots must monitor the autopilot and flight control system and communicate with ATC for any new clearances or route adaptations. Therefore, it is critical that while the pilot flying is impaired or incapacitated, the aircraft's flight parameters are kept in a safe envelope. If the autopilot disconnects, the aircraft may deviate from its intended flight profile. As a result, the auto flight system and underlying sensor system must be more robust than the current industry standard. This ensures that at least basic autopilot functionality is provided at any time, even in the case of system failures. This concept of “more robust automation” is a topic of interest in both industry and academia, with varying technology readiness levels. Airbus claims to have such robust autopilot systems already available (Airbus S.A.S., 2018, 2022)

4.2 Execution of immediate actions

Some situations require immediate flight crew action. These situations include rapid decompression, imminent collision with other aircraft or terrain, and fire on board the aircraft.

In the event of rapid depressurization, pilots must don their oxygen masks within the time of useful consciousness and initiate an immediate emergency descent to a safe altitude, typically between FL 100 and FL 140. In the case of a rapid decompression during eMCO, the PR must be awakened, and the PF and PR must immediately don an oxygen mask. Since the time of useful consciousness at altitudes above 35,000 feet following rapid decompression is only about 15 seconds (FAA, 2013), the PR must either sleep with the oxygen mask on or be able to immediately don the mask when the alert sounds. If during an eMCO phase the PF becomes incapacitated as a result of (rapid) decompression, or if pilot incapacitation is immediately followed by decompression, eMCO-capable aircraft must perform an emergency descent fully autonomous, i.e. without pilot interaction. Various OEMs have already integrated emergency descent functionality into their modern auto flight or autopilot systems, such as Airbus (Airbus S.A.S., 2022), Dassault (Dassault, 2013) and Garmin (Garmin, 2023). These systems monitor cabin pressure and automatically initiate an emergency descent to a safe altitude.

Another scenario that requires immediate pilot intervention is an imminent collision with another aircraft. In such events the Airborne Collision Avoidances System (ACAS) will generate a Resolution Advisory (RA) that must be followed immediately. Therefore, when during eMCO flight the PF is incapacitated, the autoflight system must be capable of automatically following the RA. Airbus already provided this functionality (Airbus S.A.S., 2021).

Imminent collision with terrain will not be a hazard for the majority of eMCO flights, as it is assumed the eMCO is only applied during the cruise segment of the flight. Nevertheless, certain routes may encounter areas of very high terrain, such as the L888 routing over the Himalayas. To enable eMCO flights on these routes, the aircraft must be equipped with an Automatic Ground Collision Avoidance Systems (Auto GCAS) to ensure that that a combination of PF incapacitation and aircraft drift down due to e.g. an engine failure is not catastrophic. Auto GCAS are already in operation for fighter aircraft such as the F-16 and F-35 (Lockheed Martin, 2023) and Auto GCAS has been tested for military transports and bombers, which are not able to perform the same aggressive evasive manoeuvres as fighters (Gahan et al., 2018). An alternative mitigating strategy is prevention of eMCO flights over high mountainous areas.

Fire on board must be dealt with as soon as it is detected. In the event of an engine fire, this means shutting down the affected engine and activating the fire extinguishing system. The action must be performed correctly to avoid accidentally shutting off the remaining engine. In the case of an engine fire during the eMCO phase, there is no pilot-to-pilot cross check to catch any mistakes and to ensure the correct engine is shut down. In the case of pilot incapacitation, a quick human response to an engine fire is not possible. Due to the critical nature of the situation and the irreversibility of incorrect actions, eMCO aircraft systems must be capable of autonomously handling an engine fire. A quick and automatic response is also required in case of fire areas where fire is most likely, i.e. the avionics bay and cargo area.

5. Alerting the resting pilot when the PF is incapacitated

Current crew call systems for augmented crew allow resting pilots to be called from the flight deck. Crew call systems usually consist of a warning horn and feature voice communication through handsets. In the event of a detected fire or rapid decompression scenarios, the warning horn in the crew resting area is automatically activated (Airbus S.A.S., 2005, 2022; Boeing, 2004, 2007). If the PF is only partially incapacitated and the incapacitation is self-recognised, the PF could utilize the current crew call system. In case of a sudden and complete PF incapacitation, a monitoring system (see section 3) must detect the incapacitation and automatically alert the pilot resting. To support restauration of the situational awareness of the pilot resting, information on the reason for the wake-up call (i.e. the type of emergency condition) may be useful for the PR. As the PF in this scenario is incapacitated and cannot provide information, details on the nature of the emergency must be given by a system, e.g. by defining a dedicated aural signal, or by generating a voice warning. However, sleep inertia may limit the usefulness of providing information to the PR immediately upon waking up.

6. Bringing the resting pilot back into the loop when the PF is incapacitated

If the eMCO segment is aborted because of incapacitation of the pilot flying, the pilot resting must be alerted and called back to perform flight related tasks. It is imperative that the pilot coming out of the rest period regains situational awareness (SA) and that the possible effects of sleep inertia are considered.

Upon return to the flight deck the pilot will be confronted with a situation that may initially be confusing. It is important that the pilot, even while potentially still suffering from sleep inertia, identifies whether the aircraft is in a safe state. If the aircraft is in a safe state, priority can be given to the incapacitated pilot, possibly with help from the cabin crew. The pilot resuming must diagnose the state of the incapacitated pilot and engage mitigating actions to secure the situation. This may include ensuring that the incapacitated pilot cannot obstruct flight controls and performing lifesaving actions such as the Heimlich manoeuvre or using an automated external defibrillator (AED).

In case the returning pilot calls for help from the cabin crew, there might not be a mutual understanding of each other’s roles and responsibilities. If the cabin crew member is not aware of the fact that the capable pilot has just prematurely ended a rest period and may still be suffering from sleep inertia, confusion on leadership can occur. In such a ‘leadership vacuum’ it is unclear who should be doing what, when and how (Bienefeld and Grote, 2014).

According to EASA rules for air operations, the operations manual of a CAT operator should include a statement covering the necessary coordination procedures between flight and cabin/other crew members. The abnormal and/or emergency procedures and duties should include crew incapacitation (EASA, 2023). For eMCO operations is seems logical to also include coordination procedures and duties between flight and cabin crew during aborted eMCO segments in the operations manual. In addition, it seems beneficial to discuss the mutual expectations for eMCO flights, with emphasis on unusual circumstances such as aborted eMCO segments, during pre-flight pilot to cabin briefings (Chute and Wiener, 1995).

After performing these actions, the pilot can continue regaining SA, which includes awareness on the aircraft status (current aircraft parameters, status of systems, fuel status, cabin status, and an overview of relevant changes that occurred while the pilot was resting) and awareness on the flight status (aircraft position, weather ahead, ATC clearances, fuel vs planning, any changes to the flight plan).

After the pilot has reviewed this information, a decision must be made on the continuation of the flight. Depending on the assessed criticality of the incapacitated pilot, this may be a decision to land as soon as possible.

A complicated situation occurs when the pilot is called back to the cockpit and is confronted with an incapacitated pilot and an aircraft in an unsafe state, such as a major malfunction that cannot be controlled by the autoflight system and requires immediate pilot action. The unsafe aircraft state must be recognised by the pilot resuming flight activities and the pilot needs to prioritise actions even while potentially still suffering from sleep inertia. Such events are extremely rare however and will also be challenging in a normal two-pilot operation.

Another difficult situation can occur in case of mental incapacitation of the pilot, for instance as a result of a depressive disorder or anxiety disorder. Pilots are not immune to psychiatric disorders. In a cross-sectional survey among 406 international pilots, 7.2% of the respondents reported significant symptoms of depression and anxiety (Venus and Grosse Holtforth 2022). A pilot that has an anxiety attack during an eMCO segment may be able to self-declare incapacitation, but when an anxiety attack is triggered by an event that automatically results in an eMCO abort (e.g. an aircraft system malfunction) the pilot returning the flight deck may not immediately understand that the pilot flying is not performing.

The protocol that is used to re-synchronise the pilot resting should account for all these circumstances.

7. Results of a survey on in-flight incapacitation and fatigue

To obtain information about the occurrence of flight crew incapacitation, fatigue and physiological needs in operational practice, an on-line survey was distributed across different European pilot organisations, including airlines and pilot unions. Specific topics addressed were pilot incapacitation, sleep inertia, fatigue, physiological needs, and a category “other”, which allowed the respondent to leave any additional comments on eMCO / SiPO. Demographical data were also collected. The questionnaire and all its items is included in Appendix A.

The survey was opened on 20 November 2023 and closed on 18 December 2023, allowing 6645 full responses (4646 incomplete responses were excluded). Further data processing steps involved filtering out the unrealistic values, nonsense responses, or responses that did not meet the criteria set in the question.

7.1 Demographics

On the topic of flight crew incapacitation, 6300 respondents provided useful information. Table 7-1 provides demographic data for the respondents who were included based on their responses.

Table 7-1. Demographics of survey respondents (N = 6300)

		N	%
Age	18-24	88	1.4
	25-34	1376	21.8
	35-44	2131	33.8
	45-54	1772	28.1
	55-64	909	14.4
	65+	24	0.4
Role	Captain	3317	52.7
	First-Officer	2923	46.4
	Second-Officer	60	0.9
Type rating*	Airbus A220	209	3.3
	Airbus A319 / A320 / A321	2329	37
	Airbus A330	1303	20.7
	Airbus A340	174	2.8
	Airbus A350	947	15
	Airbus A380	34	0.5
	Boeing 737 Family	1252	19.9
	Boeing 747	420	6.7
	Boeing 757 / 767	142	2.3
	Boeing 777 / 787	981	15.6
	Embraer E-Jets	199	0.3
	Other**	480	7.6

* As some of the respondents hold multiple type ratings, the percentages do not add up to 100%

** Other type ratings include for instance types from manufacturers ATR, de Havilland, Bombardier, Cessna and Dassault, and some single engine aircraft and helicopters.

Respondents on average have 18.78 (SD = 10.59, Min = 0, Max = 47) years of experience on the flight deck and 9306 flight hours (SD = 5968.34, Min = 200, Max = 32350).

7.2 Incapacitation

Figure 7.1 gives an overview of the results of the survey request to elaborate on the type of incapacitation and impairment that the participants had seen in their career. This graph shows how often a particular type of incapacitation or impairment was mentioned by the respondents. It is not a representation of how often a particular type of incapacitation or impairment occurred. If a respondent indicated to have experienced impairment by fatigue 'many times' it was counted as one mentioning. Despite this limitation, the results can be seen as a rank order under the assumption that types of incapacitation that were mentioned more often did also occur more often.

Of the 6300 survey respondents, 4161 provided useful information on the type of incapacitation or impairment. The other 2140 respondents either did not provide an answer or did not provide information that allowed classification according to the type of incapacitation or impairment of Table 2-1. For example, answers such as 'I was not fit to fly' or 'the captain was incapacitated' are not sufficiently specific to classify the type of incapacitation or impairment according to Table 2-1.

The most frequently mentioned type of incapacitation or impairment was fatigue, mentioned in 1619 of the 4161 useful responses (38.9 %). Many of those described that they had fallen asleep or had seen a crewmember fall asleep multiple times or that they had routinely experienced degraded performance due to fatigue. Many of the respondents that mentioned incapacitation or impairment by fatigue commented about exhausting rosters or complained that flight time limitations do not provide sufficient protection against fatigue.

The second most frequently mentioned type of incapacitation was gastroenteritis, mentioned in 1146 of the 4161 useful responses (27.5 %). Respondents typically indicated to have experienced incapacitation or impairment by gastroenteritis once or 'a couple of times' in their career. Most of the gastroenteritis was blamed on the quality of the food, either on-board or at the location of departure.

Infectious diseases were mentioned in 576 of the 4161 useful responses (13.8 %) as a cause of incapacitation or impairment. Influenza, Covid-19 and common cold were the most frequently mentioned diseases, with only a handful of other cases such as malaria and dengue fever. Several of the respondents that mentioned incapacitation or impairment due to an infectious disease indicated that they did not feel well before the start of the duty but decided to continue anyway because of inferior medical services at the departure location. Company pressure was also sometimes mentioned as a reason to continue the duty in spite of experiencing flu or COVID symptoms.

Otorhinolaryngological problems were mentioned in 432 of the 4161 useful responses (10.4 %) as a cause of incapacitation or impairment. Almost all of these cases involved blocked ears or sinuses, resulting in temporary loss of hearing and/or headache. There were also several cases of loss of voice, and three cases of chocking.

Headache was mentioned 95 times (2.3%). This only includes cases that referred to headache or migraine without further explanation of the cause. Cases of headache due to blocked sinuses were classified as otorhinolaryngological problems and were not classified as headache.

Musculoskeletal problems, mentioned in 64 of the 4161 useful responses (1.5 %), referred to pain in the lower back or sprained joints. Emotional stress was mentioned in 35 responses (0.8 %). Personal problems, death of a relative and family issues were mentioned as causes of emotional stress.

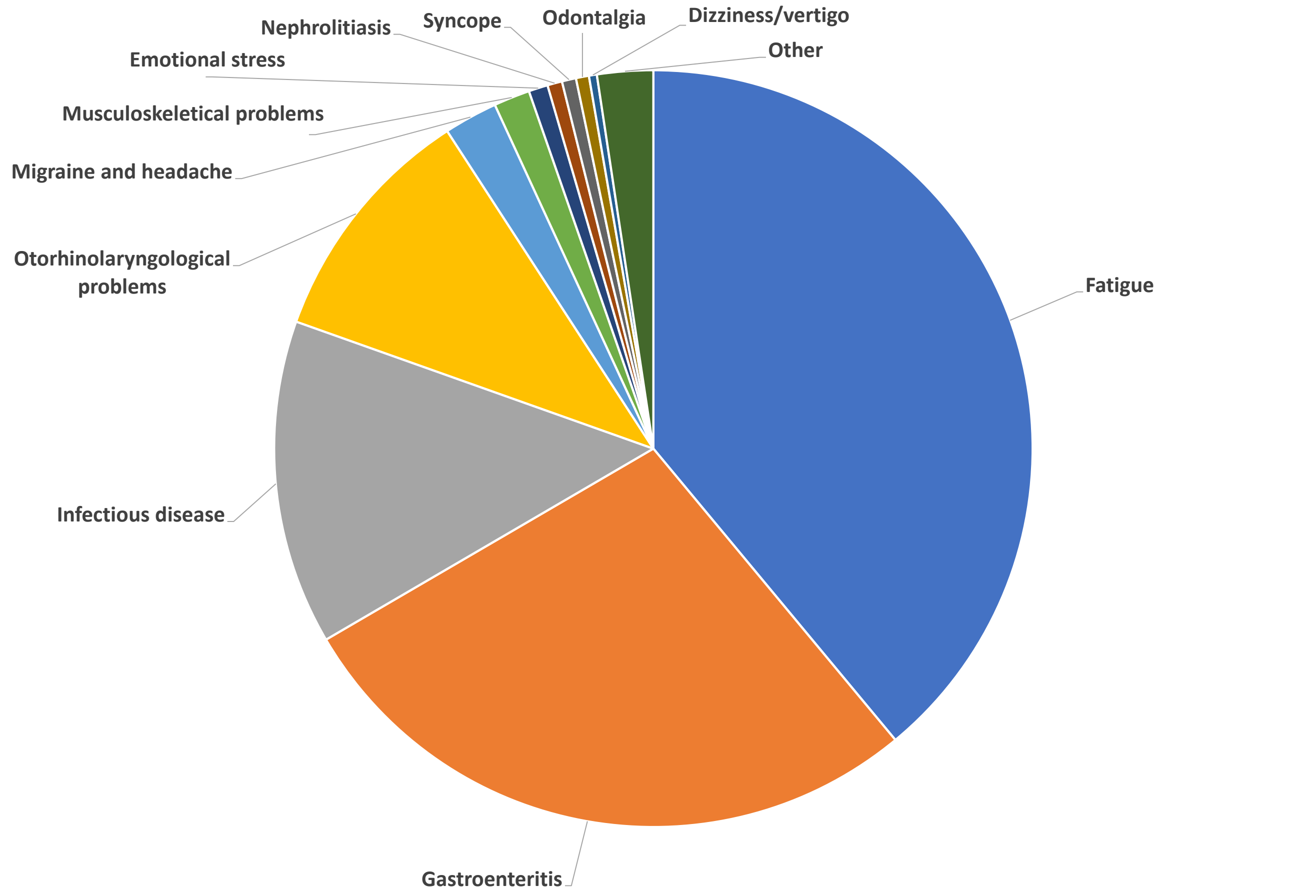

Figure 7.1. Types of incapacitation mentioned in the survey

Participants were also asked regarding the symptoms they noticed when assessing whether their colleague was fit to fly or not. From all responses, 3369 people reported noticing that their colleague had their eyes closed, 1042 noted irrational professional behaviour, 1943 individuals noticed inappropriate actions and/or reactions from their colleagues. Moreover, 2060 respondents found their colleague to be non-responsive, while 1394 individuals noted restlessness. Finally, 543 respondents observed their colleagues' pallor, noticing their skin turning pale, 2427 indicated they saw their colleague yawning, and 582 saw profuse sweating / sweating on the forehead as a symptom that led them to question whether their colleague was fit to fly. Some other symptoms were identified, ranging from noticing a colleague was in pain (though no further details were specified), irritability, and vomiting.

The frequency with which colleagues asked each other about their fitness to fly due to medical reasons varied substantially. Whereas some pilots never questioned their colleagues in that regard, other reported doing so up to 999 times in total, which can likely be interpreted as a symbolic value to represent the commonness of the situation. On average, pilots asked other pilots about their fitness to fly due to medical reasons 8.57 times during their career (*SD* = 45.13, Min = 0, Max = 999).

However, asking a colleague whether they are fit to fly due to fatigue reasons is substantially more common, with an average of 43.14 times per career (*SD* = 120.74, M*in* = 0, M*ax* = 999).

Finally, the number of times that incapacitation is experienced by crew members can be related to the years of experience (Table 7-2) and the number of flight hours (Table 7-3) of the flight crew in question. The rate of experiencing both subtle[1] and total incapacitation in other crew members and in oneself, on average, is portrayed in both tables.

Table 7-2. Rate of incapacitation-related events per year of flying experience

Number of times per year of flying experience	Mean	SD	Min	Max
Rate of asking colleague whether (s)he was fit to fly due to (suspected) medical reasons	0.47	2.23	0	90
Rate of asking colleague whether (s)he was fit to fly due to (suspected) fatigue	2.61	7.33	0	124.88
Rate of identifying subtle incapacitation of your colleague crew member	1.05	4.42	0	160
Rate of taking control of the flight due to total incapacitation of a colleague crew member	0.05	0.35	0	13.33
Rate of taking control of the flight due to subtle incapacitation of a colleague crew member	0.25	1.81	0	99.9
Rate of finding oneself ill and (almost) not fit to fly during a duty	0.69	2.52	0	90

Table 7-3 lists the number of time a certain incapacitation event occurred per flight hour as reported by the respondents to the survey. This suggests, on average, that approximately:

- Every 909 flight hours, a flight crew member asks their colleague whether they are fit to fly due to (suspected) medical reasons;
- Every 172 flight hours, a flight crew member asks their colleague whether they are fit to fly due to (suspected) fatigue reasons;
- Every 435 flight hours, a flight crew member identified subtle incapacitation in their colleague crew member;
- Every 10.000 flight hours, a flight crew member has to take control of the flight due to total incapacitation of a colleague crew member;
- Every 1.667 flight hours, a flight crew member has to take control of the flight due to subtle incapacitation of a colleague crew member;
- Every 625 flight hours, a flight crew member finds oneself ill and (almost) not fit to fly.

Table 7-3. Rate of incapacitation-related events per flight hour

Number of times per flight hour	Mean	SD	Min	Max
Rate of asking colleague whether (s)he was fit to fly due to (suspected) medical reasons	1.1×10^{-3}	5.7×10^{-3}	0	2.6×10^{-1}
Rate of asking colleague whether (s)he was fit to fly due to (suspected) fatigue	5.8×10^{-3}	1.7×10^{-2}	0	3.2×10^{-1}
Rate of identifying subtle incapacitation of your colleague crew member	2.3×10^{-3}	9.0×10^{-3}	0	2.6×10^{-1}
Rate of taking control of the flight due to total incapacitation of a colleague crew member	1.0×10^{-4}	7.0×10^{-4}	0	3.3×10^{-2}

[1] The questionnaire did not define subtle incapacitation or explain the difference between subtle and partial incapacitation. It is therefore assumed that responses for subtle incapacitation include occurrences of both subtle and partial incapacitation.

Rate of taking control of the flight due to subtle incapacitation of a colleague crew member	6.0×10^{-4}	3.8×10^{-3}	0	1.7×10^{-1}
Rate of finding oneself ill and (almost) not fit to fly during a duty	1.6×10^{-3}	6.3×10^{-3}	0	2.6×10^{-1}

7.3 Sleep inertia

7.3.1 Experiencing sleep inertia oneself

While the sleep inertia phenomenon was thoroughly described in Deliverable D-4, the present survey also aimed to shed light on pilot experiences with sleep inertia. From the 6300 complete responses, 4794 pilots reported that they have experienced sleep inertia during flight, while 1494 pilots indicated that they have no experience with it. 12 respondents skipped this question or provided nonsense answers. Those who have experienced sleep inertia mostly report experiencing this phenomenon relatively often (M = 52.82, SD = 194.54, min = 1, max = 5000), though there are substantial differences between pilots. Some pilots seem to recall very specific instances of experiencing sleep inertia, while others seem to experience it at such high frequency that an exact number cannot be given. Pilots differ substantially in their experience of the duration of long sleep inertia. On average, pilots report a sleep inertia duration of 17 minutes (SD = 16.08, min = 0.1, max = 120), ranging from several seconds up to two hours.

The symptoms of sleep inertia that are noticed by flight crew are quite diverse. Pilots report that they feel like their bodies have woken up but that their brains are still asleep. They notice that their minds are acting slow, which is reflected in slower responses to stimuli. Pilots report not being able to deal with abnormal situations, or not knowing their limits in terms of performance. Dizziness was also mentioned, and this may be difficult to recognise in others. Abnormal or incoherent responses on the other hand are often noticed in others as symptoms of sleep inertia, but can be more difficult to recognise in oneself.

Figure 7-2 presents an overview of a qualitative analysis of the own symptoms of sleep inertia for a random selection of 340 responses. The majority of responses (261 of 340) did not specify symptoms of sleep inertia, although sleep inertia was recognised a common phenomenon. For clarity these are not shown in figure 7-2. The most frequently mentioned symptoms are fatigue related (feeling tired, yawning, etc), followed by slow cognitive functioning and slow behavioural output.

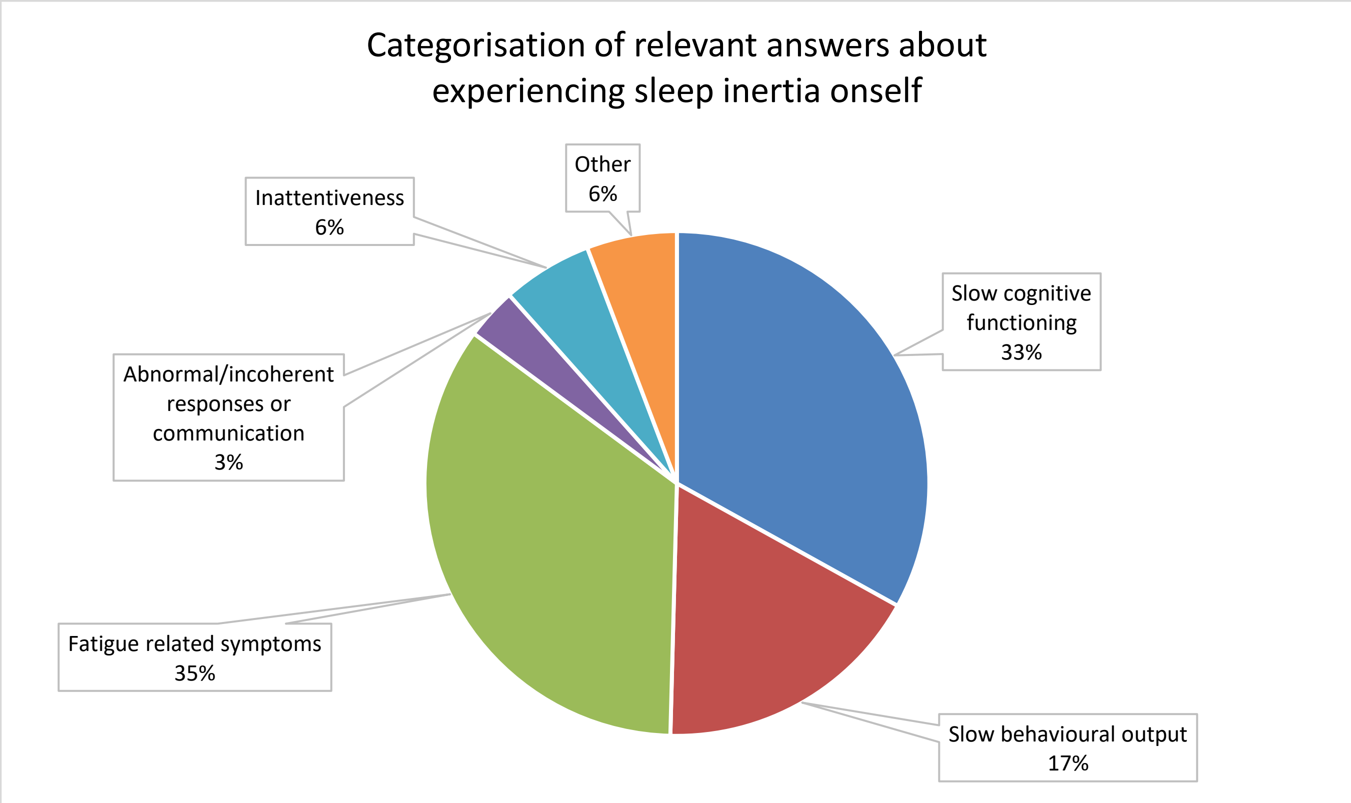

Figure 7-2. Categorisation of relevant answers about symptoms of sleep inertia, from a subsample of 340 responses

7.3.2 Recognising sleep inertia in colleagues

From the 6300 complete responses, 4305 pilots reported to have recognised that their colleagues were affected by sleep inertia, while 468 pilots reported that they had never recognised a colleague affected by sleep inertia. For unknown reasons, about 1500 respondents skipped this survey question. The results indicate that sleep inertia is a known phenomenon among most pilots and that many pilots put at least some effort in paying attention to the other pilot after they return from their rest breaks.

Figure 7-3 presents an overview of a qualitative analysis of the symptoms of sleep inertia recognised in others for a random selection of 340 responses. Symptoms that crew recognise in others are quite similar to the symptoms they experience themselves, with a slightly different perspective. Similar to own symptoms, fatigue related symptoms are most frequent. However, abnormal and incoherent responses or communication are more frequently identified for others than for oneself.

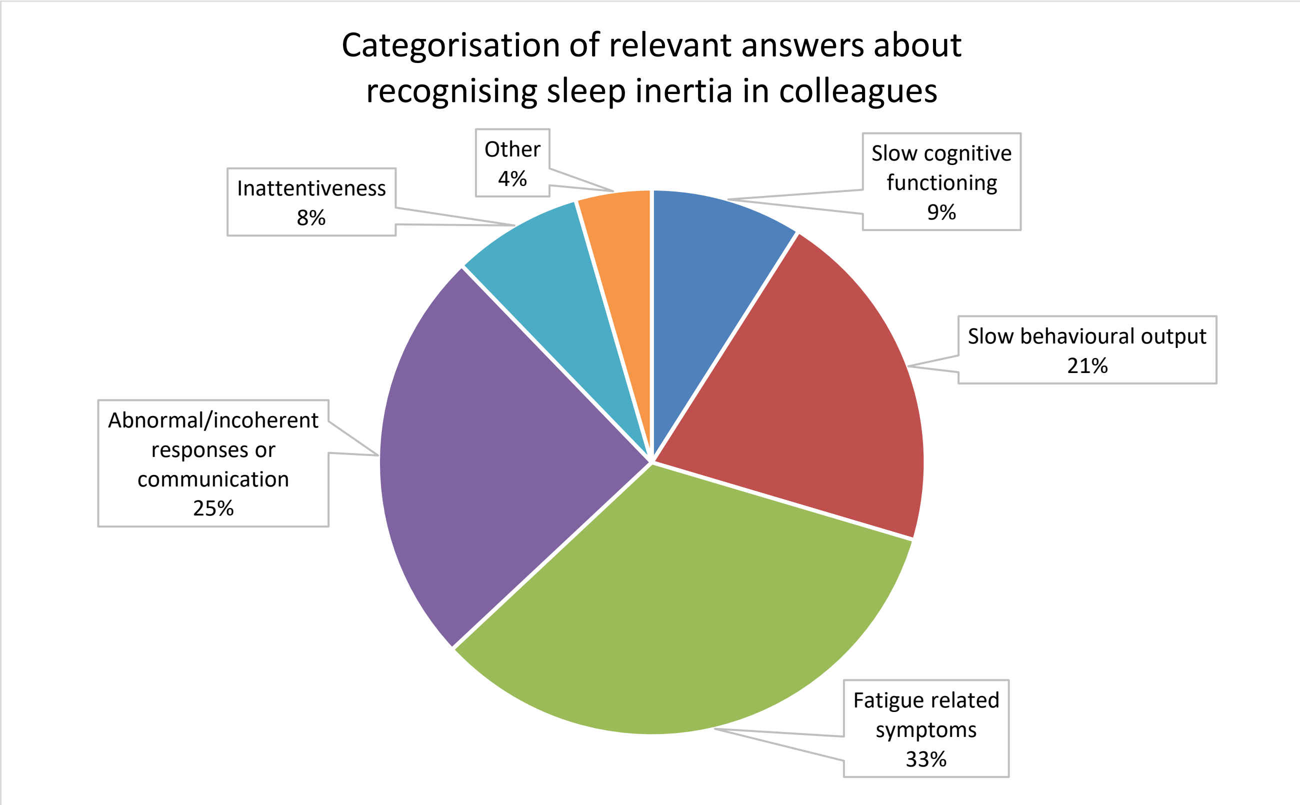

Figure 7-3. Recognising sleep inertia in colleagues, from a subsample of 340 responses

8. Potential impact on certification requirements

The potential impact of pilot incapacitation in the context of eMCO on certification requirements can be split in operational requirements related to Regulation (EU) 965/2012 and technical requirements related to Regulation (EU) 748/2012.

8.1 Technical requirements

The certification of large aircraft under EASA is arranged via Annex I of Regulation (EU) 748/2012 ('Part 21') against the Certification Specification 25 (CS-25). These certification specifications are focussed on the proper functioning of aircraft equipment and systems and the impact of those on the airworthiness of the aircraft (CS 25.1309). If a (important) system fails, the aircraft should be designed such that the aircraft can still perform a safe flight and landing and the flight crew is provided with information of these failed systems in order to take appropriate actions. In those cases, recognition and response of the failure would therefore directly affect the failure condition.

From a cognitive standpoint, prerequisites for a proper application of corrective actions are:

- adequate recognition of the failure condition,
- establishment of a valid interpretation of the situation,
- elaborate an appropriate plan of action, and
- sufficient time is available to establish an appropriate interpretation of the situation and perform the corrective action(s) necessary to address the failure condition.

These prerequisites are usually considered as implicitly given and fulfilled by default by the aircraft designer and need to be confirmed during e.g. testing.

When considering pilot incapacitation during extended minimum crew operations, these prerequisites need to be achieved by aircraft systems rather than the flight crew during the timeframe between the onset of incapacitation and the moment when a pilot can again regain control of the situation.

Any on-board aircraft system for monitoring the pilot flying, maintaining the aircraft in a safe state and alerting the pilot resting, must comply with the traditional requirements for aircraft systems. These include e.g. fire safety requirements, proper functioning and appropriate design. Most importantly, these systems must meet the requirements of CS 25.1309:

(1) Any catastrophic failure condition
  (i) is extremely improbable; and
  (ii) does not result from a single failure; and
(2) Any hazardous failure condition is extremely remote; and
(3) Any major failure condition is remote;

In an eMCO ConOps, the failure to detect pilot incapacitation must be considered a major failure condition, because it would reduce the capability of the aeroplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be a significant reduction in safety margins or functional capabilities. According to the logic used in CS 25.1309, the probability of failure to detect flight crew incapacitation must therefore be remote which is defined as having average probability per flight hour of the order of the order of 1×10^{-5} or less, but greater than of the order of 1×10^{-7}.

8.2 Operational requirements

Monitoring of the pilot and detection of incapacitation during operation, as described in section 3.1, are typically covered by the operational regulations for Flight Crew (FC). EASA part ORO (Organisation Requirements for Air Operations, Annex III to Regulation (EU) 965/2012), section FC (Flight Crew), requires pilots to be trained in the procedure for pilot incapacitation. This includes (but is not limited to) the requirements for Operations Manuals (ORO.MLR.100) and initial (e.g. ORO.FC.120)- and recurrent training (ORO.FC.130).

The operational requirements are (partially) based on the aircraft design. A typical flow down from aircraft design to operation is presented in Figure 8-1.

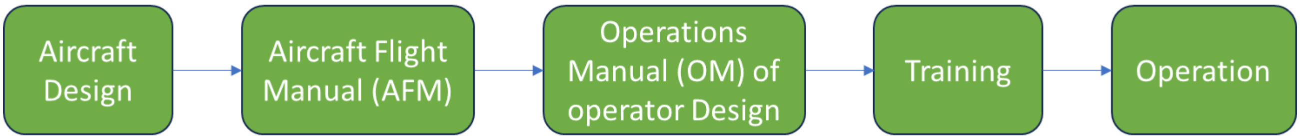

Figure 8-1: Typical flow of operational requirements from aircraft design to flight operations

If the basic aircraft type design allows eMCO operation, this information shall be available in the AFM and OM. The operator will need to adjust its training program for the inclusion of eMCO operation including special attention regarding the systems to detect incapacitation, the systems to alert the pilot resting, the process of changing from pilot resting to pilot flying (including the movement of the resting area and the flightdeck) and the systems that will control the aircraft and take decisions during that period. These trainings need to include the abnormal behaviour of these systems.

8.3 Aeromedical certification of Class 1 airline pilots

Current aeromedical risk assessment concepts for Class 1 pilots (ATPL) are aimed at mitigating the risk of in-flight incapacitation of pilots. The acceptability of this risk is based on the presence of two pilots in the cockpit. It is generally accepted that a second pilot in the cockpit is a major determinant of flight safety (DeJohn et al. 2004). In the commonly used “1% rule” risk assessment concept recommended by ICAO a 2nd pilot in the cockpit reduces this risk by a factor of 1.000 (ICAO, 2012).

The eMCO cruise flight is considered as a single pilot operation with the consequence that current EASA medical requirements exclude commercial air transport (CAT) pilots who have a medical certificate with an OML operational limitation (OML= valid only as, or with, a qualified co-pilot). This concerns quite a substantial number of pilots in the EU. Moreover, pilots aged 60-64 years will be excluded because the holder of a pilot licence who has attained the age of 60 years shall not act as a pilot of an aircraft engaged in commercial air transport except as a member of a multi-pilot crew (EASA, 2019).

Based on the above-mentioned arguments, it is clear that the current requirements do not allow an accurate estimation of the medical incapacitation risk of Class 1 airline pilots engaged in eMCO. Therefore, a new medical risk assessment concept should be developed by EASA before eMCO (and SiPO) can be implemented in commercial air transport operations.

9. Discussion and conclusion

Incapacitation can be described as a phenomenon that is distributed over two axes representing total versus partial incapacitation and subtle versus obvious incapacitation. Incapacitation can be progressive, developing from partial incapacitation to total incapacitation. In cases of partial incapacitation the pilot may be ale to self-declare the incapacitation.

In-flight incapacitation as a consequence of medical problems is a rare event occurring up to 0.45 times per 10million flight hours. There are no reliable data on partial incapacitation because it is not systematically reported. There is an increased risk of pilot incapacitation with age, although not all causes of medical incapacitation are age related. Nevertheless, prevention of incapacitation by periodical medical screening is important to minimise incapacitation risk and this should include screening on psychological issues.

Detection of pilot incapacitation will be critical technology for eMCO. There is not a specific measurement methods that allows reliable detection of all types of incapacitation. A combination of techniques will have to be used to measure vital signs and to monitor pilot activity. Self-identification of imminent incapacitation is also important and pilots may have to be educated to help recognising symptoms of imminent incapacitation. Data protection rules must be considered and robust arrangements must be in place to assure confidentiality.

The use of some sort of dead-man switch, similar to what is used in trains, may be considered. The required frequency for activating the switch can probably be lower than what is common in trains. In any case, musculoskeletal disorders and automatic response behaviour should be carefully analysed when considering a dead man switch for eMCO.

Results of an on-line survey about the occurrence of flight crew incapacitation, fatigue and physiological needs shows that the most frequently mentioned types of incapacitation were

- Fatigue
- Gastroenteritis
- Infectious diseases
- Otorhinolaryngological problems.

Fatigue is usually not seen as a type of incapacitation and is addressed separately in regulation and operational procedures. However, the frequency and the effect of fatigue on flight crew performance and flight safety warrant that incapacitation detection in an eMCO ConOps includes detection of severe fatigue.

It is critical that while the pilot flying is impaired or incapacitated, the aircraft's flight parameters are kept in a safe envelope. This means that at least basic autopilot functionality must be provided at any time, even in the case of system failures, and immediate actions must be performed automatically, including:

- Emergency descent in case of depressurization
- Execution of collision avoidance manoeuvre following a ACAS RA,
- Fire extinguishing and isolation procedures in case of engine fire, avionics fire or cargo fire.

In an eMCO ConOps, the failure to detect pilot incapacitation must be considered a major failure condition, because it would reduce the capability of the aeroplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be a significant reduction in safety margins or functional capabilities. According to the logic used in CS 25.1309, the probability of failure to detect flight crew incapacitation must therefore be remote which is defined as having average probability per flight hour of the order of the order of 1×10^{-5} or less, but greater than of the order of 1×10^{-7}.

The current requirements do not allow an accurate estimation of the medical incapacitation risk of Class 1 airline pilots engaged in eMCO. Therefore, a new medical risk assessment concept should be developed by EASA before eMCO (and SiPO) can be implemented in commercial air transport operations.

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Appendix A Survey

Extended Minimum Crew Operations – Single Pilot Operations (eMCO SiPO)

Dear sir/madam,

Welcome to this survey about pilot incapacitation and physiological needs during extended Minimum Crew Operations (eMCO), and Single Pilot Operations (SiPO).
This survey is one of the surveys that is set out to the pilot community by researchers of the EASA funded project that aims to assess the issues and the feasibility of the implementation of both eMCO and SiPO in the EU regulatory framework.
The questions is this survey are in particular focussed on "incapacitation of pilot flying", "sleep inertia", "fatigue" and "breaks due to physiological needs".
Next to this survey, this project comprises interviews, workshops and experiments to gather more detailed information and ideas from the pilot communities.
The aim of the survey is to gather a broader opinion of the pilot community about the topics mentioned above, and consists of mainly multiple-choice questions. However, some open questions are also included in which you can elaborate on your answers.

There are 31 questions in this survey.

Informed consent

Participation is voluntary and you can stop your participation at any time. All data gathered via this survey will remain confidential and be processed anonymously, and will be treated according to the General Data Projection Regulation (GDPR). Moreover, all data will be disposed after the end of the study.

If you decide to participate in this survey, please confirm by clicking "yes" in this informed consent form. With this, you indicate that you have understood the information on the previous page and consent to participation in the study.

Please choose **only one** of the following:

- Yes
- No

Demographics and practical questions

How old are you?

Please choose **only one** of the following:

- 18-24
- 25-34
- 35-44
- 45-54
- 55-64

- 65 and over

How many years of experience as a pilot do you have in total?

Please write your answer here:

- _____ year(s)

How many flight hours do you currently have (all types)?

Please write your answer here:

- _____ hours

What is your current function?

Please choose **only one** of the following:

- Captain
- First-Officer
- Second-Officer
- Other _____

What type rating(s) do you currently hold?

Please choose **all** that apply:

- Airbus A220
- Airbus A319 / A320 / A321
- Airbus A330
- Airbus A350
- Airbus A340
- Airbus A380
- Boeing 737 family
- Boeing 747
- Boeing 757 / 767
- Boeing 777 / 787
- Embraer E-Jets (E170, E175, E190, E195, and E2 series)
- Other: _____

In case of (subtle) incapacitation

*Subtle incapacitation has been defined by ICAO as a "reduced state of alertness, a mental preoccupation which may result in a lack of appreciation of significant factors, increased reaction time, and impaired judgement".

Have you ever experienced the situation that you noticed that your colleague was about to become (subtle) incapacitated (i.e. not fit to fly)? Which of the items below have you ever used to assess whether your colleague is fit to fly?

Please choose **all** that apply:

- Having their eyes closed
- Irrational professional behaviour
- Inappropriate actions/reactions
- Being non responsive
- Restlessness
- Pallor (skin turning pale)
- Yawning
- Profused sweating (sweat on forehead)
- Other: _____

How often have you asked your colleague whether (s)he was fit to fly?

Please write your answer(s) here:

- Due to (suspected) medical reasons _____
- Due to (suspected) fatigue _____

How often have you identified subtle incapacitation of your colleague crew member?

Please write your answer here:

- _____ times in your career

How often have you had to take control of the flight due to **total incapacitation** of a colleague crew member?

Please write your answer here:

- _____ times in your career

How often have you had to take control of the flight due to **subtle incapacitation** of a colleague crew member?

Please write your answer here:

- _____ times in your career

How often have you found yourself ill and (almost) not fit to fly during a duty?

Please write your answer here:

- _____ times in your career

Please elaborate on the situation(s) above if applicable

Please write your answer here:

____

Sleep inertia

Sleep inertia is the phenomenon of experiencing impaired cognitive and sensory-motor performance that is present directly after waking up.

Have you ever experienced sleep inertia yourself during flight (e.g. following a period of in-flight or controlled rest)?

Please choose **only one** of the following:

- Yes
- No

How frequently have you approximately experienced sleep inertia?

Please write your answer here:

- _____ times in your career

How long did the sleep inertia last, approximately?

Please write your answer here:

- _____ minutes

Have you ever recognised sleep inertia in other flight crew during flight?

Please choose **only one** of the following:

- Yes
- No

How did you recognise sleep inertia in your colleague(s)?

Please write your answer here:

____

Please elaborate on your experience(s) with sleep inertia.

Please write your answer here:

____

Fatigue

Some of the following questions are about Controlled Rest (CR). CR is when *one flight crewmember is temporarily relieved of operational duties, and takes a short, in-seat rest break, during which he or she closes his (or her) eyes and attempts to sleep. CR enables a flight crewmember to use a period of low workload to obtain a brief period of sleep and thereby improve alertness and performance, particularly for later, more critical phases of flight such as descent and landing* (Flight Safety Foundation, 2018).

How often does any crewmember on any of your flights use Controlled Rest when feeling fatigued?

Please write your answer here:

- During _____ % of your flights

What safety relevant issues have happened during the use of Controlled Rest? (i.e. missed ATC calls, deviation from clearances, difficulty of staying awake, etcetera…)?

Please write your answer here:

____

How often do you use Controlled Rest when feeling fatigued during flight?

Please write your answer here:

____

How often did you have trouble staying awake while your colleague was in Controlled Rest?

Please write your answer here:

- During _____ % of times my colleague was in controlled rest

Have you ever unintended fallen asleep while flying?

Please choose **only one** of the following:

- Yes
- No

How often have you fallen asleep while flying?

Please write your answer here:

____

For how long do you approximately sleep when you fall asleep during flight?

Please write your answer here:

- _____ minutes

If you were asleep and you were alerted, how long would it take you to wear an oxygen mask?

Please write your answer here:

- _____ minutes

Physiological needs

What is your approximate interval between toilet breaks during the flight?

Please write your answer here:

____

Do you schedule your toilet breaks in a certain way?

Please choose **only one** of the following:

- Yes
- No

What do you do in order to schedule your toilet breaks?

Please write your answer here:

____

Other

In case you have any other considerations regarding eMCO SiPO, (subtle) incapacitation, sleep inertia, fatigue or physiological needs during flight that you would like to say, please type them below.

Please write your answer here:

____

Thank you very much for your participation to this survey!
If you have any questions or if you want to discuss any topics further with one of the researchers, please use the following contact details: info@emco-sipo.eu.

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