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Pilot Medical Monitoring: State of the Science Review on Identification of Pilot Incapacitation

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16. Abstract

Organizations have begun to explore the use of human physiological monitoring technologies in critical safety systems to mitigate risk and adapt to evolving operator concepts. This report describes the initial capabilities needed to support safe flight operations in the case of an incapacitated pilot. We describe aspects of a pilot's physiological state which, in the absence of a second flight deck crewmember, would instead need to be monitored through sensing technology. We review the maturity of the science of sensing technologies for incapacitation detection. Six types of incapacitation were identified to review the state of the science for incapacitation detection technology: sudden cardiac death, sleep, epileptic seizure, stroke, hypoxia, and acute pain syndrome.

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Abstract

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1 Introduction

Pilot incapacitation may be obvious (e.g., complete loss of consciousness) or subtle (e.g., petit mal seizure) but can result in significant risk to aircraft operation. Flight crew apply the “two communication” rule, which states that crew should suspect a potential incapacitation event if the individual does not respond appropriately to two verbal communications or if the individual responds with significant deviation from standard operating procedure (SOP) (International Civil Aviation Organization [ICAO], 2012). Nonresponse to cues or deviation from SOPs can be used as an indicator of potential incapacitation. Although cue and action sequences (e.g., button press) can be an effective tool to ensure pilot attention, such methods could increase cognitive burden and assume that all aircraft equipment is functioning correctly.

Based on information in the public domain about the industry’s interest in reduced crew operations, as well as feedback from the Research, Engineering, and Development Advisory Committee Subcommittee for Aviation Safety, the Federal Air Surgeon sponsored a research requirement addressing pilot incapacitation monitoring requirements. The Office of Aerospace Medicine (AAM) submitted this research requirement to The MITRE Corporation’s Center for Advanced Aviation System Development (MITRE CAASD) under Outcome 4, which is focused on Safety and Training. AAM requested that this requirement be included in the Fiscal Year 2022 funding, and the OneAVS Governance Board prioritized it.

Advances in sensing and autonomy have the potential to increase safety further. In the long-term, advances could help support reduced crew operations and/or allow for increased inclusivity of pilots with some medical conditions or medical risks. Organizations have begun to explore the use of these technologies in safety-critical systems to improve outcomes (e.g., driver fatigue monitoring), but careful consideration is needed before recommending the use of current technologies in aviation environments.

Consistent with Federal Aviation Administration (FAA) Order 8040.4B Safety Risk Management Policy, a risk assessment requires estimates of the likelihood and severity of each identified hazard or failure mode to determine the need for mitigations; for those failure modes assessed as high (unacceptable) risk, mitigations must be developed to reduce the risk to a manageable level. Physiological monitors may provide such risk mitigations. The degree of mitigation depends on their respective effectiveness.

This report describes the initial capabilities needed for an incapacitation system to support maintained safe operations. It reviews the maturity and validity of current technologies for detecting six incapacitation types: sudden cardiac death, epileptic seizure, stroke, sleep, hypoxia, and acute pain syndrome. This report is not intended to cover all physiological monitoring technologies or capabilities but provides the initial review to inform the next steps to support the use of technologies for aviation safety.

2 Incapacitation Signal Sensor Requirements

Each pilot on a two-pilot flight deck, composed of the Pilot Flying (PF) and the Pilot Monitoring (PM), can recognize some physiological "failures" in their teammate. Much of the ability to recognize such physiological failures is assumed—that is, as a basic human ability to recognize that another is not performing at full capacity. More specifically, this recognition task depends primarily on observation and communication. In the case of observation, one of the pilots will *see* that the other's actions are either delayed or absent, imprecise, of the wrong magnitude, or altogether incorrect. Similarly, in the case of communications, one of the pilots will hear that the other's responses are either delayed or absent, incoherent, or altogether inappropriate.

The outcome of a physiological failure—its severity—depends on the phase of flight and the actions being performed by the crew at the time of failure.

In future flight deck concepts, some of the tasks performed by crews today will be automated. In the current study, we assume such capabilities have been incorporated to some extent; the details of such implementation are beyond the scope of this report. We consider two cases:

> Case 1: The physiological failure occurs in such a way that the pilot suffering the failure recognizes their problem and alerts the other human or automated crew with sufficient time for a cooperative passing of control of the aircraft to the other.
>
> Case 2: The physiological failure occurs in such a way that the pilot suffering the failure does not recognize their problem, and the other human or automated crew must independently identify the failure and assume control of the aircraft without a cooperative passing of control.

In the current two-human flight deck, these two cases manifest in this way.

> Case 1: The PF recognizes their own physiological "failure" and asks the PM to take control; the PM takes control. This assumes that the time to recognize the failure is less than the time required for the next critical pilot action.
>
> Case 2: The PF suffers a physiological "failure" before they can communicate it to the PM; the PM can observe the physiological "failure" of the PF and assume control without confirmation communications or actions from the failure pilot.

In a future one-pilot context, automation performs the tasks of the copilot, and *technology* must replace those copilot detection activities—that is, it must perform the *observational detection tasks* that the copilot formerly performed.

> Case 1: The PF recognizes their own physiological "failure" and *directs aircraft automation* to take control; the aircraft takes control (via automation or remote control). No physiological monitoring is needed for these handoffs, which already commonly occur on the flight deck.
>
> Case 2: The PF suffers a physiological "failure" before they can communicate it to the aircraft. The pilot's physiological monitoring sensor array must observe the physiology "failure" of the PF, interpret it correctly, and initiate automated flight control in cases where the PF cannot self-report that "failure." The aircraft takes control without confirmation communications with the failure pilot. Each pilot physiological "failure mode" can be expressed as a set of physiological **signals**. Detecting each failure mode's set of signals is the **requirement**. A **solution set** is a combination of sensors that can

meet the requirement. The minimum essential list (i.e., the minimum solution set) is the smallest set of sensors that meet the requirement.

Only Case 2 generates sensor requirements when there is a human-machine team on the flight deck; that is when sensors must interact with automation to perform the tasks previously performed by a copilot. These situations are the focus of this paper.

Each pilot’s physiological “failure mode” can be expressed as physiological **signals**. Each of these failure modes “emits” the combination of physiological signals unique to that mode. This can be shown in the mapping matrix depicted in Figure 2-1. In this matrix, white cells indicate no association, lighter shading and the letter *I* are used to indicate signals that are indirectly associated with an incapacitation event, and darker shading and the letter D is used to indicate signals that are directly associated with an incapacitation event.

	Physiological “Failure Modes”					
Signal	Sudden Cardiac Death	Sleep	Epileptic Seizure	Stroke	Hypoxia	Acute Pain Syndromes
S1-Blood Oxygen Level	D				D	
S2-Cardiac Waveform	D	I				I
S3-Brain Activity	I	D	D	D	I	
S4-Movement & Muscle Tone		D	D	D		I
S5-Respiratory Waveform	D				D	I
S6-Responsiveness & Speech		D	D	D		

Figure 2-1: Failure-Signal Matrix, where D= Direct and I = Indirect Sensing of the Incapacitation

Sensors can detect one or more of the signals associated with physiological failure. This mapping is shown in Figure 2-2 using the same six sensors shown in Figure 2-1. Similar to Figure 2-1, indirect sensing methods would be less useful in the early detection of the associated signal. For example, a cardiac waveform (S2) can be detected by a pulse oximeter and heart rate (HR) sensing device, such as an electrocardiogram (ECG).

	Sensing Devices						
Signal	Pulse Oximeter	Heart Rate ECG	EEG	Body Position	Facial Imaging	End-Tidal CO_2	Responsiveness Challenges
S1	D						
S2	D	D					
S3			D		I		
S4				D	D		
S5	I	I	I			D	
S6							D

Figure 2-2: Signal-Sensor Matrix where D= Direct and I = Indirect Sensing of the Incapacitation

Detecting each failure mode's set of signals is the **requirement**. A **solution set** is any combination or an array of sensors that can meet the requirement. We can express the requirements and solution sets using connectors, as shown in Figure 2-3.

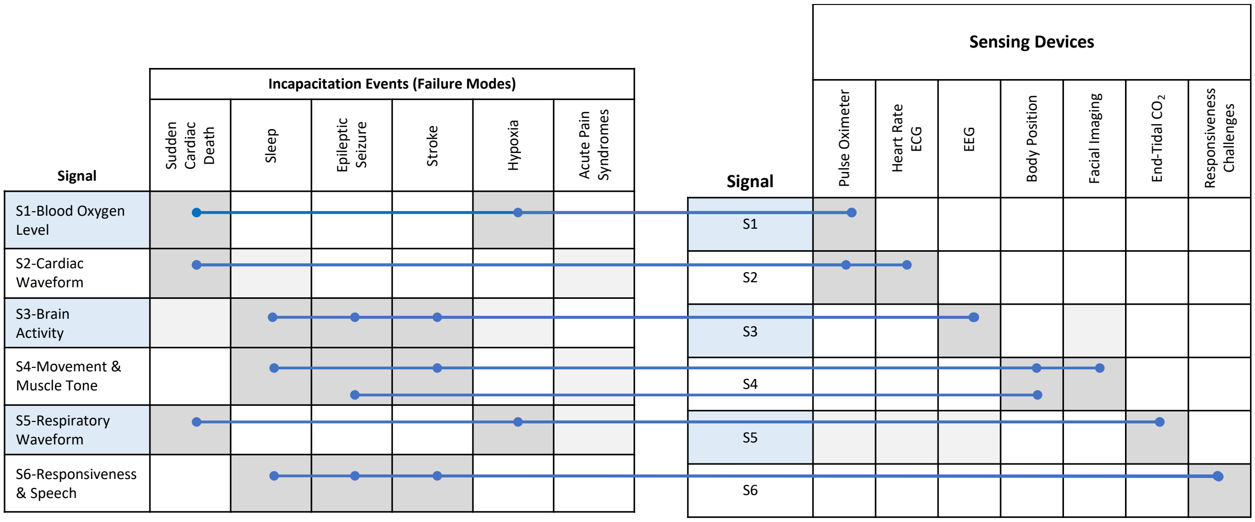

Figure 2-3: Signal to Sensor Coverage for Failure Modes

For example, monitoring Sudden Cardiac Death is satisfied by signals S1, S2, and S5, blood oxygen level, cardiac waveform, and respiratory waveform, respectively (blue connector lines above).

The minimum essential list (the minimum solution set) is the smallest set of sensors that meet the requirements. Then we can convey a minimum equipment list as a minimum critical subset of this solution set, as shown in Figure 2-4. The lighter shading for acute pain syndromes indicates that the sensors reviewed do not have specific, early sensing capability for acute pain, based upon Figure 2-1 and Figure 2-2.

	Sensor Coverage						
Failure mode	Pulse Oximeter	Heart Rate/ECG	EEG	Body Position	Facial Imaging	End-Tidal CO_2	Responsiveness Challenges
Sudden Cardiac Death	D	D				D	
Sleep			D	D	D		D
Epileptic Seizure			D	D			D
Stroke			D	D	D		D
Hypoxia	D					D	
Acute Pain Syndromes		I		I		I	

Figure 2-4: Sensor Coverage Matrix where D= Direct and I = Indirect Sensing of the Incapacitation

3 Scope and Methods

In-flight pilot incapacitation can result from many factors, including physiologic changes that prevent a pilot from conducting normal duties during a flight (ICAO, 2012). For this document, pilot incapacitation will be considered from the standpoint of physiologic factors, not those that may occur because of external factors like a bird strike and the effects of laser light on vision.

The incapacitation types focused on in this study were identified by examining the literature. A review of several studies (Booze, 1989) examined the common causes of incapacitation and patterns that should be considered in policies to reduce potential accidents. A review of in-flight incapacitation and impairments of United States airline pilots from 1993 to 1998 identified 39 incapacitations and 11 impairments, with the most common categories of incapacitation being a loss of consciousness, cardiac, neurological, and gastrointestinal (Dejohn et al., 2004). A review of aviation from 1960 to 1966 identified epileptiform manifestations, coronary occlusions, and renal/ureteric colic as the most common categories of incapacitation (Buley, 1969). In two self-reported surveys (1968 and 1988), pilots reported acute gastroenteritis (e.g., food poisoning) as the most common cause of incapacitation accounting for 75% of instances (ICAO, 2012). A 2012 review of United Kingdom/Joint Aviation Requirements professional pilot license holders found 36 incapacitations, half being cardiac, four sudden death, and multiple psychiatric (ICAO, 2012).

3.1 Incapacitation Events

Based on information from the literature, MITRE CAASD focused on the following incapacitation events for this paper:

- sudden cardiac death
- epileptic seizure
- stroke
- sleep
- hypoxia
- acute pain

This paper considers psychological events, such as panic attacks, out of scope. While potentially possible to detect (e.g., hyperventilation and elevated HR), individual baselining would likely be needed to support accuracy, and the presentation of the psychological event could vary significantly between individuals. Pilot deviation from expected actions could potentially be used to help support detection, but the system would need to consider the possibility that the aircraft sensors calculating the expected actions could be faulty.

The use of active pilot engagement, such as cueing a pilot to answer a question or push a button that triggers automation (as is used by Garmin Autoland), is not the focus of this paper. For this document, we limit the analysis to conditions where the rapidity of onset precludes a copilot notification or an autopilot activation.

To evaluate appropriate technologies and the state of the science, MITRE CAASD conducted a technology and literature review of available devices that can measure one or more of the identified biometrics for detecting incapacitation. The space of commercially available and in-development wearables used in research is vast. Following the initial examination of the space, MITRE CAASD focused the review on the state of the science for detecting incapacitation event signals, as shown in Table 3-1.

Table 3-1: Signals for Incapacitation Events

Primary Physiologic System Affected	Incapacitation Event Examples	Incapacitation Signals
Cardiovascular	**Sudden cardiac death**	Nonresponsive, altered or no cardiac waveform, altered or no respiratory waveform, altered or no brain activity, slumping, pallor, blood oxygen level
Neurological	**Sleep, epileptic seizure, stroke**	Altered responsiveness, slumping, eyelid position, altered brain activity, muscle rigidity (tonic-clonic seizure), loss of muscle tone (akinetic seizure, sleep), cessation of movement (absence seizure), hemodynamic changes, slumping, agitation, slurred or strange speech, asymmetric loss of muscle tone, facial asymmetry
Respiratory	**Hypoxia**	Altered responsiveness, poor cognition, reduced reaction time, agitation leading to loss of consciousness
Other	**Acute pain syndromes**	Altered responsiveness, pain, increased heart rate, increased blood pressure, increased respiratory rate, agitation, altered posture

Sensing modalities are intended to measure one or more incapacitation signals. For example, although a pulse oximeter is primarily used to measure blood oxygen levels, it can also measure HR, hemoglobin levels, and carboxyhemoglobin levels. **Error! Reference source not found.** lists incapacitation signals, some of their corresponding sensing modalities, and a few representative examples of currently available devices.

Table 3-2: Sensing Modalities and Examples

Incapacitation Signal	Sensing Modality	Sensor Examples
Blood Oxygen Level	SpO_2, flight deck oxygen sensors	Masimo, Fly Sentinel, Garmin Vivo Smart, Astroskin
Cardiac Waveform (blood pressure and/or heart rate)	Sphygmomanometer, plethysmograph, ECG, heart rate monitor, SpO_2	Masimo, Fly Sentinel, AWARE, Garmin Vivo Smart, Astroskin
Brain Activity	EEG, cognitive challenges, speech challenges	Cerebrotech, Zeit Medical, BIS
Movement and Muscle Tone	Body position sensors, flight control motion sensors, accelerometer, facial imaging, muscle tone sensor, seat position sensors, flight control pressure sensors	NeurAlert, Smart Chair, Fatal Recognition, Tobil, Myoton

Incapacitation Signal	Sensing Modality	Sensor Examples
Respiratory Waveform	ECG, end-tidal CO_2 detector, respiratory rate detector, SpO_2	Equivital
Responsiveness and Speech	Responsiveness challenges, speech assessment	Interrogative queries through flight control systems

Note. SpO_2 = oxygen saturation; ECG = electrocardiogram; EEG = electroencephalogram.

3.2 Evaluation Criteria

Initial evaluation criterion for device inclusion in this report was the ability of a device to measure one of the following: blood oxygen level, cardiac waveforms, eye tracking, neural activity, or posture. The field of wearable technology is rapidly expanding and advancing, and this review is not intended to be all-inclusive. Instead, it is meant to present various options for incapacitation monitoring in a flight deck setting and provide a framework for evaluating the viability of such technologies. As an initial standardized evaluation of technology, the level of maturity and validity for device evaluation were defined as shown in Table 3-3 and Table 3-4. While many physiologic sensing technologies can be used across multiple incapacitation event types, they typically evaluate distinct features in the physiology and thus are considered separately in this report.

Table 3-3: Maturity Assessment Criteria

Maturity Assessment	Score
Commercially available and intended for aviation use	5
Commercially available for non-aviation use	4
Commercially available for laboratory use	3
Not commercially available but operationally tested	2
Not commercially available or operationally tested	1

Table 3-4: Validity Assessment Criteria

Validity Assessment	Score
Accuracy established in aviation use case	5
Accuracy established in aviation-like environment	4
Accuracy established in non-aviation environment	3
Accuracy established in laboratory environment	2
Accuracy unknown; no peer-reviewed publications	1

4 Technology for the Detection of Incapacitation Events

Using the representative incapacitation events listed earlier (sudden cardiac death, epileptic seizure, stroke, sleep, hypoxia, and acute pain), signals and exemplar technologies are discussed in terms of their validity and maturity in this section. There is some overlap between incapacitation events and the types of signals that could be used, but this would be expected and aligns with an overarching objective to find a minimum number of sensors to detect events of interest.

4.1 Sudden Cardiac Death

Sudden cardiac death is the main cause of sudden death. Sudden cardiac death is a natural death that occurs with a sudden loss of consciousness within an hour of symptom presentation (Mantziari et al., 2008). Sudden cardiac death accounts for 6% to 20% of all deaths in the United States, varying by age (Stiles et al., 2021). The presentation and detection of a sudden death share many characteristics of other incapacitation events. This includes lack of motion/muscle tone, absent cardiac waveform, absent respiratory waveform, low-to-absent oxygen saturation (SpO_2), hypothermia, absent brain activity, and absent pupillary reactivity.

4.1.1 Cardiac Waveform

While cardiac death may occur before the loss of cardiac electrical signals (i.e., loss of circulation) (Shemie & Gardiner, 2018), continuous electrocardiographic monitoring is commonly used in the hospital setting. Alarms are triggered if the cardiac waveform is abnormal (e.g., ventricular tachycardia, premature ventricular contractions, etc.). False alarms and overly sensitive thresholds by systems are a significant concern and potential burden to hospital clinical staff (Pelter et al., 2020). Potential solutions for this issue have been proposed, including softening thresholds to not flag non-actionable cardiac changes and customizing alarm threshold settings to the patient population (Fujita & Choi, 2020). These problems are likely exacerbated in an aviation environment where movement and strong vibrations can disrupt electrical and optical sensing of cardiac waveforms.

Asystole is one of the primary cardiac waveforms that should be detectable in an aviation environment. Asystole is the lack of electrical signal from the heart. While asystole may be falsely identified due to loose-fitting sensors or the removal of wearable devices, it is a clear cardiac presentation of sudden death. Wearable cardioverter defibrillator systems detect asystole and provide defibrillation. One example system, the LifeVest from Zoll Systems, collects ECG signals and uses an asystole threshold of HR <10 beats per minute during a 16-second sampling window (Garcia et al., 2021).

In addition, research in laboratory environments indicates that optical (i.e., photoplethysmography) measurements from wearable devices (e.g., CardiacSense watch) can also detect induced ventricular tachycardia/fibrillation or transient ventricular asystole (Chorin et al., 2021).

MITRE CAASD evaluated the maturity of automated cardiac waveform assessment for sudden death as **4. Commercially available for non-aviation use** and the validity as **3. Accuracy established in non-aviation environment** since devices exist to support detection and intervention in real-world environments, including home use of wearable cardioverter defibrillator systems by high-risk populations.

4.1.2 Respiratory Waveform

Respiratory function is a good indicator of health status. A respiratory rate (RR) ≥ 25 or ≤ 8 breaths per minute is associated with patient decline (Rolfe, 2019). In the case of sudden death, breathing may lag circulatory arrest but is expected to stop within a few minutes after sudden cardiac death (Shemie & Gardiner, 2018).

For the detection of sudden death, only a respiratory waveform is needed. The presence of breathing has been investigated to support emergency rescue scenarios (Pramudita et al., 2022) and the detection of sudden infant death (Zhao et al., 2016).

Respiratory function is conventionally measured using observation; that is, counting to calculate RR (Rolfe, 2019). Spirometry is the gold standard for evaluating respiratory function (i.e., a person breathing into a tube with their nose plugged), but this would not be practical for continuous monitoring of pilot health. Instead, respiratory belts can be placed on the chest and measure the displacement of the chest due to breathing. These sensors are often paired with ECG sensors on the chest (e.g., Zephyr). RR can also be estimated from the cardiac waveform, though this method can have high levels of error (Hartmann et al., 2019; Meredith et al., 2012). Stand-off optical methods using thermography (i.e., heat from the breath) or visually sensing movement of the chest have also been developed (Meredith et al., 2012). MITRE CAASD evaluated the maturity of automated respiratory waveform assessment for sudden death as **3. Commercially available for laboratory use** and the validity as **4. Accuracy established in aviation-like environment** since devices exist to support detection and intervention in real-world environments.

4.1.3 Blood Oxygen Level

Peripheral blood oxygenation (i.e., SpO_2) is typically maintained near 100%. A drop in blood oxygenation is a good predictor of death (Hwang et al., 2013; Mejía et al., 2020), and single blood oxygenation measurement has been able to detect mortality from multiple causes (Vold et al., 2015), including sudden death (Bateman et al., 2008). Similar to cardiac waveforms, SpO_2 alarms (e.g., 15 seconds at 90% blood oxygenation) are commonly used in a hospital setting, and researchers have investigated strategies to reduce false alarms and alarm fatigue, including the potential benefits of individualized alarm thresholds (Lansdowne et al., 2016). Wearables, including the Apple Watch, can increasingly monitor SpO_2 with reasonable accuracy (Pearson Correlation Coefficient R = 0.81) for monitoring health status in controlled environments (Pipek et al., 2021). Groups are also investigating stand-off methods, such as optical camera systems for measuring SpO_2, among other vital signs, with reported errors of less than 1% when the individual is still and in laboratory conditions (Selvaraju et al., 2022). Additional information about SpO_2 monitoring in an aviation environment can be found in Section 4.5.

MITRE CAASD evaluated the maturity of automated blood oxygen assessment for sudden death as **4. Commercially available for non-aviation** use and the validity as **3. Accuracy established in non-aviation environment** since studies associating blood oxygenation and death have been done in a hospital environment.

4.1.4 Brain Activity

Outside of direct brain trauma, brain death typically lags cardiac death. Consciousness and electroencephalography (EEG) activity is lost within 30 seconds of circulatory arrest, although a loss of electrical activity (i.e., isoelectric EEG) may occur prior to circulatory arrest in hypoxic states (Shemie & Gardiner, 2018). MITRE CAASD evaluated the maturity of EEG for sudden death as **4. Commercially available for non-aviation use** and the validity as **3. Accuracy established in non-aviation environment** since studies associating EEG and death have been done in a hospital environment.

4.2 Epileptic Seizure

While uncommon, there have been cases of latent epilepsy in pilots (Refai, 2012). Epileptic seizures are a result of excessive or abnormal brain cell activity. They may present in multiple ways, including involuntary muscle movement (e.g., “convulsive” epilepsy), absence staring, or auras. Seizures can be sustained over multiple minutes, and individuals may also experience impaired consciousness during recovery (Chen et al., 2013). Overall, detection of incapacitation due to convulsive epilepsy through movement or EEG is fairly mature, but detection is limited for other presentations of epilepsy.

4.2.1 Brain Activity

Measurement of brain activity is the conventional method for the identification of epilepsy. Preliminary research suggests that commercially available mobile EEG technologies, like Emotiv EPOC (https://www.emotiv.com/epoc/) and Epitel Epilog (https://www.epitel.com/), can be used to support epilepsy detection (Frankel et al., 2021; Titgemeyer et al., 2020). Epitel Epilog uses a small sensor placed on the forehead or neck and is not yet cleared by the Food and Drug Administration (FDA) for ambulatory use. It requires a clinician-in-the-loop for seizure identification, although Epitel is working on an automated seizure detection algorithm.

EEG devices exist for in-hospital use with a clinical review. The space of mobile seizure detection is rapidly advancing. However, motion/muscle activation artifacts, the need for conductive gel (i.e., wet electrodes) (Tatum et al., 2021), and/or sensor comfort (e.g., dry electrodes) (Lopez-Gordo et al., 2014) may affect translation into an aviation environment. MITRE CAASD evaluated the maturity of ambulatory EEG for epilepsy detection as **4. Commercially available for non-aviation use** and validity **3. Accuracy established in non-aviation environment** due to the significant non-aviation use of the systems. As dry electrodes advance to reduce signal noise and user discomfort, they could be a beneficial addition to health status monitoring.

4.2.2 Movement and Muscle Tone

Devices exist for the detection of convulsive epilepsy. The Empatica Embrace2 (https://www.empatica.com/) is an FDA-cleared wrist-worn device for epilepsy detection. The sensor detects seizures using movement, electrodermal activity, and variation in the skin's electrical characteristics due to sweating and notifies caregivers when a seizure has been detected. The device is not intended to be worn during physical activity due to the risk for false positives and is not intended to detect nonconvulsive epileptic events. MITRE CAASD evaluated the maturity wrist-worn devices for convulsive seizure detection as **4. Commercially available**

for non-aviation use and validity **3. Accuracy established in non-aviation environment** due to the availability of an FDA approved device.

4.2.3 Responsiveness and Speech

A common presentation of epilepsy is the lack of response. Pilot-controller communications and mutual understanding are essential. As a result, pilots acknowledge each radio communication with air traffic control (ATC) by using the appropriate aircraft call sign (Federal Aviation Administration, n.d.). While delayed or a lack of ATC communication may be a sign of incapacitation; there may be long periods of flight where no communication is needed and other situations, such as radio failure or incorrect frequency, that affect communications. MITRE CAASD evaluated the maturity of acoustic response for epilepsy detection as **1. Not commercially available or operationally tested** and validity **1. Accuracy unknown; no peer-reviewed publications**.

4.3 Stroke

Approximately 795,000 individuals in the United States experience a new or reoccurring stroke each year (Saini et al., 2021). An example of pilot incapacitation during flight due to a stroke is the April 2021 ANA Boeing 787-8 flight from Paris to Tokyo. Eight hours into the flight, the first officer observed the captain presenting with sudden facial asymmetry and headache; the flight was diverted and landed safely (Curran, 2021).

The early warning signs of a stroke include movement and muscle tone asymmetry, including in the face (e.g., smiling) and slurred speech (Centers for Disease Control and Prevention, 2022). Time is a critical part of the reduction of the effects of stroke on functional outcomes leading researchers and clinicians to prioritize early detection.

4.3.1 Movement and Muscle Tone

Wearable inertial measurement units (IMUs; e.g., accelerometers, magnetometers, and/or gyroscopes) may be used to detect movement asymmetry associated with stroke. An example is Neuralert Home (https://www.neuralerttechnologies.com/), a wrist-mounted sensor for monitoring upper extremity movement asymmetry in a hospital setting. The system has FDA Breakthrough Designation but is not yet commercially available. MITRE CAASD learned through correspondence that Neuralert research is currently in review for peer-reviewed publication. The website claims the device can detect 65% of strokes within 30 minutes and 94% within 80 minutes. Since this device was developed for stroke identification in hospitalized patients, it is unclear how the device algorithms would perform in an aviation environment with different movement patterns and intensities. A 2017 review demonstrated that wearable IMUs could support monitoring posture and upper extremity movement after stroke in clinical and home environments (Wang et al., 2017).

In addition to upper extremity assessment, a review by Mobbs et al. (2022) determined that gait can be accurately assessed with single inertial measurement units, including for individuals who have suffered a stroke. Most researchers place these sensors on the lower back, but other locations include the wrist, ear, and foot. Apple calculates gait metrics, including steadiness and asymmetry, on iPhones with iOS 15+ (Apple, 2022). While Apple describes the use of these metrics to support recovery tracking post-stroke (Apple, 2021), they do not discuss potential use for early stroke detection. Additionally, since pilots spend most of their time seated during flight, gait assessment could not be used for stroke detection during much of the time the pilot performs the mission.

MITRE CAASD evaluated the maturity of accelerometer-based stroke detection as **2. Not commercially available but operationally tested** since devices exist that have received FDA review and been tested in clinical environments but are not yet commercially available for stroke detection, and the validity as **3. Accuracy established in non-aviation environment** mainly due to the large amount of work on movement asymmetry in rehabilitation. Significant testing would be needed to validate in an aviation environment and to ensure sufficient sensitivity and specificity from using movement asymmetry to detect early signs of stroke. MITRE CAASD recommends focusing on upper extremity movement asymmetry due to the limited time pilots spend walking around the aircraft. Models may need to leverage individual or population baselines for aviation populations to control for expected movement patterns and intensity in aviation environments.

Facial asymmetry is related to movement asymmetry but is best evaluated with image-based sensing methods. One example of this technology is Fatal Recognition, a freely available Android application developed by the Hong Kong Stroke Association that evaluates facial asymmetry to detect early signs of a stroke (Little Black Book, 2019; The Hong Kong Stroke Association, 2020). The application can scan for facial asymmetry when the individual unlocks their mobile phone. No publications were identified about the accuracy of Fatal Recognition for stroke detection. A review of the automated image-based assessment of facial nerve function (e.g., through resting and voluntary movement symmetry assessment) identified several instruments with a wide range of reported accuracy (49.9% to 95.5%) (Lou et al., 2020). However, at the time of the review, none were being used clinically due to the limited clinical validation (Lou et al., 2020).

MITRE CAASD evaluated the maturity of image-based stroke detection as **4. Commercially available for non-aviation use** since the Fatal Recognition application is available for download and use for early detection of stroke. Validity is evaluated as **3. Accuracy established in non-aviation environment**, but significant additional validation is needed against clinical ground truths to support clinical use. Overall, the current state of the science indicates that facial image-based assessment could be an effective tool to include as a part of pilot incapacitation sensing system. The noncontact nature of this sensing method is an additional benefit for limiting the burden on pilots. One potential concern that would need to be examined to support its use in aviation is the effect of sunglasses on the accuracy of the algorithms.

4.3.2 Brain Activity

Several research groups are examining the potential of neurological signal-based stroke detection. One example is Zeit Medical (https://www.zeitmedical.com/), a wearable headband-mounted EEG sensor for detecting stroke or seizure during sleep. The system leverages machine learning algorithms to detect stroke-related abnormal EEG patterns. No peer-reviewed publications were identified through PubMed and Google Scholar searches, and the device is neither commercially available nor FDA-cleared for stroke diagnosis or screening. A review by Sutcliffe et al. (2022) of EEG for stroke diagnosis showed promise for the technology with a reported area under the curve (AUC) from 0.81 to 1.00, where 0.8 to 0.9 is considered excellent. Only one study included data within six hours of symptom onset, so additional data are needed to support early detection. The transition of this capability from a home or clinic sleep environment to an aviation environment may also be problematic due to movement artifacts and increased cognitive activity. Research has shown the difficulty of flight deck EEG-based workload detection due to current hardware limitations (Dehais et al., 2019).

Another neurological monitoring technology developed by Cerebrotech Medical Systems leverages an FDA-cleared head-mounted system to measure volumetric impedance phase shift. Cerebrotech can complete an assessment in 30 seconds. In their study, they could differentiate severe from minor stroke with 93% sensitivity (AUC 0.93) (Kellner et al., 2018). Though they collected data from healthy controls, they did not report on the diagnostic ability for differentiating minor strokes from the control population. The reported mean bioimpedance for each group (severe stroke [N=57] 16.5%, 95% CI 14.6 to 18.4; minor stroke [N=26] 8.0%, 95% CI 6.9 to 9.0, healthy adults [N=79] 5.0%, 95% CI 4.5 to 5.5) suggest that differentiation between minor stroke and health populations may be possible. While the device provides a quick assessment for stroke, it is not currently intended for continuous monitoring, and the device profile would likely be prohibitive for aviation use.

MITRE CAASD evaluated the maturity of neurological signal-based stroke detection as **2. Not commercially available but operationally tested** since devices have been tested with clinical populations, and systems have received FDA clearance. They graded the validity as **2. Accuracy established in laboratory environment** since testing was done in highly controlled environments that were not directly equivalent to real-world use (e.g., time post-stroke onset) and since information supporting accuracy is limited. Significant testing would be needed to ensure accuracy in the aviation environment.

4.3.3 Responsiveness and Speech

The final sensing modality of stroke considered in this report is speech abnormalities. Pennsylvania State University (PSU) has developed a smart phone–based screening test that performs in less than four minutes. The 2020 International Conference on Medical Image Computing and Computer-Assisted Intervention proceedings and a PSU news article state that the model was built using speech data from 80 individuals who had suffered a stroke. The test demonstrated 93% sensitivity and 79% accuracy when evaluated using video data collected in the emergency room and compared to clinical tools used by emergency room doctors (Hallman, 2020; Yu et al., 2020). A brief review of machine learning algorithms for automatic aphasia assessment identified many studies in several languages that have had variable success (e.g., one study reported 43.3% accuracy, while another reported a 0.931 true positive detection rate) (Mahmoud et al., 2021).

MITRE CAASD evaluated the maturity of automated speech analysis for stroke detection as **1. Not commercially available or operationally tested** due to the limited information available supporting operational use and the validity as **2. Accuracy established in laboratory environment** since there is limited data supporting accuracy of speech-based stroke detection and studies to date have had variable results. For use in the aviation use case, a speech analysis system would ideally evaluate general speech and not require specific phrases to be spoken as a part of an assessment.

Overall, stroke detection technologies are a promising emerging field, but additional research is needed to support accuracy and cost-effectiveness (Lachance & Ford, 2019) and applicability in an aviation environment.

4.4 Sleep

Although it is not normally a state of concern, as the other conditions discussed in this paper are, a pilot falling into a sleep state can adversely affect the safety of commercial air travel just as much as any other incapacitating condition. According to a 2016 survey, 59.3% of pilots reported daytime sleepiness, and 90.6% reported fatigue while flying (Reis et al., 2016). In June 2022, two pilots fell asleep on a flight from New York City to Rome, triggering fears of a terror attack (ABC7, 2022). Other than the loss of direct communication, there are several methods by which one can determine whether a subject has fallen asleep. Before falling asleep, individuals show signs of fatigue such as difficulty keeping eyes open, yawing, frequent blinking, loss of concentration, and nodding off. These signs become more prevalent as the individual's fatigue increases and they fall asleep (Albadawi et al., 2022). Although some of these signs can be early indicators of impending incapacitation, for this document, signs indicating current incapacitation will be discussed.

4.4.1 Cardiac Waveform

As a person enters a sleep state, their HR and RR will decrease, and their HR variability will increase as the body enters a parasympathetic state. However, finding the exact point at which an individual is asleep using these metrics is difficult, as all these effects also occur in an individual who is simply becoming more relaxed. A fatigue study during the window of circadian low (i.e., between 2 and 6 AM) with commercially rated pilots found a statistically significant difference in HR in the first and final five minutes of flight simulation, during which some of the pilots fell asleep. However, there was no statistically significant difference over the time of the flight simulation (Wilson et al., 2020). This experimental result exemplifies the difficulty in establishing a specific threshold at which one can determine sleep by HR alone. However, it also verifies that photoplethysmography (PPG) can be used as an accurate and appropriate proxy for ECG to detect HR in a simulated aviation environment.

There are two possible approaches to detecting a change of state from wake to sleep using only ECG or PPG: setting a global threshold or an individualized one. A global threshold would be the same for all users, which simplifies the process greatly but will likely have more false positives and false negatives for particular pilots. Due to the tradeoff between false positives being an irritant to the pilot versus false negatives endangering the flight, a global threshold would likely be set at a relatively high HR to minimize false negatives. An individual threshold would maximize true classification of sleep and wake states, with the caveat that each pilot would be required to undergo a baseline period to establish normal HR values for the pilot in their sleep and wake states.

Numerous devices measure ECG (MICROS, Equivital Wearable ECG) or PPG (Fly Sentinel, Garmin VivoSmart 4), and some measure both (Astroskin, HMAPS Monitoring System). The most directly applicable device to this use case, the Oura ring (https://ouraring.com/), has deployed a nap-detection system that uses HR, skin temperature, and movement to detect sleep, but it does not provide an alert until after the period of rest when it asks the user whether they were asleep. Due to the existence of nap detection algorithms using PPG, MITRE CAASD evaluated the maturity of this technology as **4. Commercially available for non-aviation use**, and its validity as **3. Accuracy established in non-aviation environment** because it has not yet been used in an aviation environment.

4.4.2 Movement and Muscle Tone

Based upon the discussion in Sections 4.2.2 and 4.3.1, MITRE CAASD evaluated the maturity of image-based sleep detection as **4. Commercially available for non-aviation use** since applications can detect facial variances. Validity is evaluated as **3. Accuracy established in non-aviation environment,** but significant additional validation is needed against clinical ground truths to support use in an aviation environment. Overall, the current state of the science indicates that facial image-based assessment could be an effective tool to include as a part of a pilot incapacitation sensing system.

4.4.3 Brain Activity

EEG is often used in sleep studies to monitor the different stages of sleep, of which there are four. The ideal pilot-monitoring system would be able to detect the first phase of sleep and issue an alert to wake the pilot, but this phase is often difficult to detect, as it is largely a transition state and is similar both to an individual who is awake but in a relaxed state and to one who is awake but simply becoming drowsy (Borghini et al. 2014). For practical purposes, the detection of the second sleep phase should be considered, as it has more distinct characteristics than the first. Stage 1 sleep is characterized by an increase in alpha waves (8 – 12 Hz), shortly after that followed by an increase in theta wave (4 – 7 Hz) activity. Stage 2 sleep is characterized by more theta wave activity that is occasionally interrupted by rapid alpha wave activity, referred to as “sleep spindles,” or large increases in signal amplitude that are referred to as “K-complexes” (Spielmen et al., 2020). Increased alpha and theta activity can be regarded as a sign of possible sleep, while the appearance of sleep spindles and K-complexes can be taken to mean the subject is asleep.

Typical EEG sensors are not suitable for an operational environment, but wireless dry-EEG sensors such as the DSI-7 by Wearable Sensing (n.d.) have the potential to fit under any required headgear without obstruction.

MITRE CAASD evaluated the maturity of neurological signal-based sleep detection as **3. Commercially available for laboratory use** since commercially available devices have been tested and evaluated during simulated flight experiments but are geared more towards fatigue detection than specifically sleep detection. The validity was evaluated as **3. Accuracy established in non-aviation environment** because EEG is often used for sleep studies and similar research experiments. Significant testing would be needed to ensure accuracy in a real aviation environment.

4.4.4 Responsiveness and Speech

Similar to the discussion in Sections 4.2.3 and 4.3.3, a common presentation of sleep is the lack of response. Pilot-controller communications and mutual understanding are essential. As a result, pilots acknowledge each radio communication with ATC by using the appropriate aircraft call sign (Federal Aviation Administration, 2022). While delayed or a lack of ATC communication may be a sign of incapacitation; there may be long periods of flight where no communication is needed. MITRE CAASD evaluated the maturity of acoustic response for sleep detection as **1. Not commercially available or operationally tested** and validity **1. Accuracy unknown; no peer-reviewed publications**.

4.5 Hypoxia

The Mayo Clinic defines hypoxia synonymously with hypoxemia as “a below-normal level of oxygen in your blood, specifically in the arteries” (Mayo Clinic Staff, 2022). A normal blood oxygen level is typically defined by a SpO_2 level of at least 95%, as measured by a pulse oximeter. The FAA expands this definition to “a state of oxygen deficiency in the body sufficient to impair the function of the brain and other organs,” which is a similar but broader definition in the sense that a state of hypoxia could be different for different individuals (Hackworth et al., 2003).

Hypoxia is a significant concern in aviation. One well-known example is the 2005 Helios Airways Flight 522 incident, where hypoxia incapacitated the flying crew, resulting in the death of all 121 individuals onboard (Hellenic Republic Air Accident Investigation & Aviation Safety Board, 2006). There are four different types of hypoxia: hypoxic hypoxia, hypemic hypoxia, stagnant hypoxia, and histotoxic hypoxia. Each has a different mechanism, but each results in the same external symptoms and loss of physiologic function (Boshers, 2015).

The United States Naval Air Systems Command (NAVAIR) defines the following as the symptoms of hypoxia: anxiety/euphoria, breathing difficulty, dizziness, fatigue, loss of muscle coordination, mental confusion, nausea, numbness, poor judgment, tingling/twitching, unconsciousness, and visual impairment (Shender, 2018). By the time an individual is experiencing symptoms, they are already hypoxic, so early detection is of the utmost importance for this condition.

4.5.1 Blood Oxygen Level

SpO_2 measurement is the leading metric to detect hypoxia, and NAVAIR provides ranges of no concern (94% or greater), low concern (87%–94%), and high concern (below 87%). The low concern range indicates a danger of becoming hypoxic, and the high concern range indicates an individual who has already become hypoxic, even if they do not exhibit outward symptoms yet. In a hospital setting, oxygen saturation is typically measured by a pulse oximeter that goes on the tip of the finger of the patient being monitored. A 2016 study of pulse oximeter alarms on intensive care unit patients experimented with decreasing the SpO_2 threshold and increasing lag time before an alarm was sounded for hypoxia, and similar methods may be helpful in determining how to minimize the false positive rate when detecting hypoxia in a flight deck setting (Scully et al., 2016). Several recently developed wearable devices have built-in pulse oximeters. Some of these devices are worn on the wrist (e.g., WHOOP, Fly Sentinel, Garmin VivoSmart, etc.), while others may be worn on other parts of the body (e.g., AWARE chest patch, PocketNIRS visor, HMAPS armband, etc.). The commercial pilot use case would require a pilot to use only one of these devices to measure oxygen saturation directly; however, redundancy could be critical, as pulse oximeters are often subject to motion-generated signal noise and artifacts, which can be greatly magnified due to vibration in a flight deck setting.

MITRE CAASD evaluated the maturity of direct hypoxia detection via blood oxygen levels as **4. Commercially available for non-aviation use** and the validity as **3. Accuracy established in non-aviation environment** due to standard and consistent use in most medical settings. Further testing would be required to ensure continued accuracy in the aviation environment.

4.5.2 Flight Deck Environment

Additionally, flight deck oxygen sensors can be an indicator that the environment itself is becoming hypoxic, which would soon cause an individual to be hypoxic as well. This indicator does not rely on the pilot's individual condition but rather their surroundings, and thus would not be helpful in the case of a pilot becoming hypoxic due to disease or other factors that are not immediately environmentally related. However, a 2009 Travel Weekly analysis determined that pilots will frequently simply ignore flight deck alarms and continue operations despite the warning (Fabey, 2009).

MITRE CAASD evaluated the maturity of flight deck oxygen sensors as **5. Commercially available and intended for aviation use** and the validity as **5. Accuracy established in aviation use case** because these sensors are already deployed in many flight deck environments.

4.5.3 Respiratory and Cardiac Waveform

Another indicator of hypoxia is increased RR. NAVAIR considers RRs between 6 and 18 breaths per minute to be normal, 18 to 25 breaths per minute to be of moderate concern, and any RR over 25 breaths per minute to be of great concern. Elevated HR is another potential indicator of an individual who is becoming hypoxic. During a study that measured the physiology of pilots at altitude, Linnville et al. (2021) found that HR increased by 23 beats a minute on average as SpO_2 levels dropped from 98% to 75%. This is consistent with the NAVAIR findings that elevated HR may indicate that a pilot will soon experience a physiological event such as incapacitation. While they can both be indicators, RR and HR alone are not enough to ensure detection of a hypoxic state, as these metrics could be altered by factors other than hypoxia.

Most wearable devices that can measure RR also measure HR (e.g., Equivital Wearable ECG, Astroskin, WHOOP), but the reverse is not necessarily the case (e.g., Polar H10, AWARE, Garmin VivoSmart). HR may also be calculated via a mounted camera monitor such as the rPPG by Noldus (2019). While this device will not detect RR, using an off-body monitor takes the onus from the pilot, who would otherwise be encumbered with a wearable device. HR and RR can be elevated by many factors such as stress and mental or physical activity, so false positive rates would need to be considered for use in an aviation environment. It could potentially be an additive component of a detection algorithm to help confirm the detection of a hypoxic state and appropriate action by the autonomous system (e.g., descent).

MITRE CAASD evaluated the maturity of HR/RR-based hypoxia detection as **4. Commercially available for non-aviation use** because numerous devices detect these signals for sports and everyday activities. The validity was evaluated as **3. Accuracy established in non-aviation environment** since testing and validation have been performed outside of an aviation setting. Further testing would be required to ensure sufficient accuracy on a flight deck.

4.5.4 Brain Activity

Hypoxia can additionally be detected via EEG, where a decrease in amplitude of alpha, beta, gamma, and theta frequencies indicates hypoxia. Importantly, Rice et al. (2019) documented that many pilots in their study could not perceive hypoxia detected by EEG, which suggests that EEG may provide a warning while there is still sufficient time to act. Typical EEG sensors are not suitable for an operational environment, but wireless dry-EEG sensors such as the DSI-7 by Wearable Sensing have the potential to fit under any required headgear without obstruction.

Snider et al. (2022) demonstrated that data transmitted from a dry-EEG sensor could be fed into several classification algorithms to detect hypoxia.

MITRE CAASD evaluated the maturity of neurological signal-based hypoxia detection as **2. Not commercially available but operationally tested** since commercially available devices have been tested and evaluated during simulated flight experiments but are not specifically designed for hypoxia detection. The validity was evaluated as **2. Accuracy established in laboratory environment** since testing was done in highly controlled environments that were not directly equivalent to real-world use, and information supporting accuracy is limited. Significant testing would be needed to ensure accuracy in a real aviation environment.

4.6 Acute Pain Syndromes

Acute pain syndromes occurring on the flight deck include gastroenteritis, cholelithiasis, nephrolithiasis, and vertebral disc herniation. In two self-reported surveys (1968 and 1988), pilots reported acute gastroenteritis, such as food poisoning, as the most common cause of incapacitation, accounting for 75% of instances (ICAO, 2012). Pain can manifest in multiple ways, such as tingling, stinging, burning, and shooting sensations (National Institutes of Neurological Disorders and Stroke, 2020). Pain can be debilitating for any duration. It is difficult to measure pain due to the subjective and relative nature of clinical scales (Jensen et al., 2017)

Researchers are seeking to provide quantitative measures of pain to support research into pain interventions. Medical devices and wearables offer potential promise to support pain management (Chen et al., 2021; Leroux et al., 2021). Many sensing methods focus on chronic pain measurement through changes in daily activities and sleep (Avila et al., 2021), which may not be relevant to pilot incapacitation.

For this document, acute pain syndromes are defined as those that can cause sudden debilitating pain, where the rapidity of onset and the severity of the pain precludes notification of a copilot or activation of an autopilot.

4.6.1 Cardiac Waveform

Pain increases HR and decreases HR variability, though this has shown mixed sensitivity across different pain types due to other factors that affect HR and HR variability, such as anxiety and stress (Leroux et al., 2021). In combination with other signals (e.g., skin conductance for the analgesia nociception index), the accuracy of pain measurement may be improved, but this has not yet been confirmed with research (Chen et al., 2021). Due to concerns about the many factors that affect physiology, the association between physiologic measurement and pain is clearest when the individual is unconscious (e.g., during surgery) (Chen et al., 2021).

MITRE CAASD evaluated the maturity of cardiac waveform pain detection as **1. Not commercially available or operationally tested** and validity as **1. Accuracy unknown; no peer-reviewed publications** since the application of current knowledge and technology (e.g., surgical monitoring of pain) is not currently translatable to environments where multiple factors (e.g., alertness, stress, physical movement) will affect the cardiac waveform metrics (e.g., HR and HR variability).

4.6.2 Respiratory Waveform

Pain increases RR (Leroux et al., 2021). While RR can be estimated from the cardiac waveform or measured using a respiratory belt, like the cardiac waveform, RR will be affected by other factors such as alertness, stress, and physical activity. A retrospective study of paramedic-measured vital signs and pain presentation found a weak but significant correlation (R=0.15) between RR and self-reported pain score; RR greater than 25 breaths per minute was associated with severe pain (Bendall et al., 2011). The authors noted that the findings were not strong enough to support clinical use for pain severity assessment.

MITRE CAASD evaluated the maturity of respiratory waveform pain detection as **1. Not commercially available or operationally tested** and validity as **1. Accuracy unknown; no peer-reviewed publications** since limited work has been done focused on RR, and the findings are not strong enough to support clinical use (Bendall et al., 2011).

4.6.3 Movement and Muscle Tone

In some acute pain presentations (e.g., gastrointestinal), the pilot may need to leave the seat or flight deck. Chair-based occupancy sensors could be used to confirm that the pilot is in a position to operate the aircraft. Occupancy sensors are commonly used in cars to support the appropriate deployment of airbags (i.e., Automotive Occupant Classification Systems). More sophisticated methods are also available. For example, the BeBop Advantage Sensor (BeBop Sensors, 2016) leverages computer vision techniques on full seat pressure “images” to identify the occupant’s position and movement. This technology is also available for passenger seat occupancy monitoring on aircraft (Diehl Aviation, 2018).

MITRE CAASD evaluated the maturity of movement and muscle tone pain detection as **5. Commercially available and intended for aviation use** and validity as **5. Accuracy established in aviation use case**. Although the sensors would not directly measure pain, they would be able to accurately identify that the pilot can no longer operate the aircraft.

Technologies for quantifying pain or identifying pain-specific incapacitation are immature. While respiratory and cardiac waveforms show some promise for pain monitoring during surgery, confounding factors will likely prevent use in the aviation environment in the near term. Seat occupancy sensors may be able to serve as a proxy due to the likely presentation of severe pain resulting in changes in posture/position in the aircraft, though the incapacitation will be missed if the pilot remains upright in their seat.

5 Comparison of Technologies

While the maturity and validity of a technology will depend on the use case, there is the potential for sensing methods and the resulting signals to be applicable across multiple incapacitation events. Table 5-1 summarizes the previously reported incapacitation detection maturity and validity assessments by incapacitation signal.

Table 5-1: Summary Table of Incapacitation Sensing Maturity and Validity

Incapacitation Signal	Incapacitation Event	Maturity Score	Validity Score
Cardiac Waveform	Acute Pain Syndromes	1	1
	Sleep	4	3
	Sudden Cardiac Death	4	3
Respiratory Waveform	Acute Pain Syndromes	1	1
	Hypoxia	4	3
	Sudden Cardiac Death	4	3
Blood Oxygen Level	Hypoxia	4	3
	Sudden Cardiac Death	4	3
Brain Activity	Epileptic Seizure	4	3
	Hypoxia	2	2
	Sleep	3	3
	Stroke	2	2
	Sudden Cardiac Death	4	3
Movement and Muscle Tone	Acute Pain Syndromes	5	5
	Epileptic Seizure	4	3
	Sleep	4	3
	Stroke	2	3
Responsiveness and Speech	Epileptic Seizure	1	1
	Sleep	1	1
	Stroke	1	2

While the sensor modalities may overlap between incapacitation types, this does not ensure maturity and translation of commercially available sensing capabilities between incapacitation event types. For example, wearables with high accuracy for cardiac waveform-based sleep detection may have a higher error in high-movement situations that they were not designed to address.

6 Recommendations

As this report has demonstrated, there are existing technologies that have the potential to be used within aircraft to monitor pilot physiological parameters associated with incapacitation as well as trigger automated aircraft operations should pilot incapacitation occur. As society and the aviation industry begin to rely upon more advanced automation, MITRE CAASD recommends that future work expands on the material presented in this report in several ways. First, MITRE CAASD recommends delineating the requirements and assessment criteria for physiologic monitors that will be placed onboard aircraft, so that clear guidelines are in place to evaluate candidate sensors and sensor suites. Second, we recommend developing a framework for considering special issuances in a future environment where physiologic sensors and automation become more commonplace. Finally, additional recommendations for further work are listed for evaluating sensors and sensing strategies in the detection and prediction of pilot incapacitation, so that resources can be applied strategically, and frameworks are established before their need. These recommendations are detailed in the sections that follow.

6.1 Establish Requirements for Incapacitation Sensing Devices

Many factors will affect the potential use of physiological sensors and associated algorithms for incapacitation monitoring on a flight deck. Devices will likely require software that integrates their outputs to be FAA certified. Since hardware and software have separate FAA certification guidelines, the software that integrates physiological signals to detect incapacitation would undergo a separate assessment for each device used to detect the physiologic signatures.

Although the devices assessed would likely fall under the scope of Simple Electronic Hardware (SEH) as defined in FAA Order 8110.105A (2017), because the failure of an incapacitation system could lead to catastrophic harm in the event of an emergency, the Design Assurance Level of many of these SEHs could fall under Level A. This would require comprehensive tests to ensure functionality under foreseeable conditions. The software that performs communication or calculations using the physiological data from these devices could be classified as Level A, as defined in FAA Order 8110.49A (2018), depending on actions taken by the software, such as sending messages to dispatch or controlling the aircraft.

Level A software requires a high degree of FAA involvement for certification and additional, comprehensive tests to ensure functionality and determine possible failure modes. The Level A classification is a worst-case scenario in terms of introducing these devices and software into a flight deck setting, and they are only likely to be classified as Level A software and hardware if flight safety is contingent on these new components. If, however, the addition of the physiological sensors and associated software is deemed only to enhance the safety of the flight, the classifications would be of the “having no safety effect” category (i.e., not interfering with normal operations), which would substantially truncate the timeline to complete certification.

While the technical requirements have not yet been developed, assumptions are provided in Table 6-1.

Table 6-1: Identified Initial Assumptions for Capability Requirement and System Interactions

	Description of Assumed Capability Requirements and System Interactions
Form Factor	Incapacitation detection equipment does not interfere with the fit of pilot oxygen masks or other items commonly used in flight (e.g., headsets, glasses). Incapacitation detection equipment does not prolong the process of donning a quick-donning type oxygen mask.
Rugged Technology	The technology described is not affected by conditions of noise, vibration, turbulence, ambient temperature, and pressure encountered during cruise operations and may also have to function for at least a limited duration following failures that result in degraded functioning of the aircraft electrical system, the onset of rapid decompression, or the appearance of smoke or fire on the flight deck. Using supplemental oxygen does not adversely impact the ability to detect incapacitation.
Actionable Information	Technology to detect incapacitation of the pilot (i.e., flying and resting) will effectively inform action to mitigate safety risks (e.g., autonomy, remote action, recall of resting pilot).
Timely Information	Technology to detect incapacitation of the pilot with sufficient speed to maintain safety, which will depend on the phase of flight. We assume that a pilot returning to the flight deck from rest requires 30 minutes to recover from sleep inertia and become familiar with the flight's situation to assume command. This could result in increased detection sensitivity in certain phases of flight to ensure the pilot can assume their responsibilities when action is needed.
Appropriate Communication	In the event of an incapacitation, the technology that identifies it could trigger appropriate notifications to ATC and the dispatch facility exercising operational control over the flight.
Balance of Human-Computer Interaction	The pilot can test that the system is working correctly. Once incapacitated, a pilot does not become available for any duty during that flight. While people sometimes quickly recover, this initial assumption would be the conservative approach ensuring sufficient screening of the pilot's health state prior to resuming duties. This must be balanced against the risk of false alarms and the potential burden on the remaining pilot or other crew to evaluate the health status of the pilot. If future safety studies prove a need for augmenting the flight crew with a person on the ground following an inflight incapacitation, the requisite airborne and ground systems technologies and procedures exist.
Regulations	The aircraft type design certification specifies a minimum flight crew of one pilot during cruise operations. For the existing airline fleet, this would mean an amendment to the type design certification and possibly an amendment to the type design itself and, therefore, modifications of the affected airframes. National and international (ICAO) regulations and standards would be modified (1) to permit the reduction of the minimum required number of pilots on the flight deck during the cruise phase of flight and (2) to reduce the number of pilots required for long-haul operations.
Other	Aircraft involved in unaugmented long-haul operations could be limited to those requiring Extended-range Twin-engine Operations Performance Standards status, which means they would have an increased and documented mechanical reliability over the general airline fleet. The aircraft can carry sufficient supplemental oxygen. 14 CFR §121.333 (Supplemental oxygen for emergency descent and first aid; turbine engine powered airplanes with pressurized cabins, 2020) requires a lone pilot on the flight deck to don

	Description of Assumed Capability Requirements and System Interactions
	their oxygen mask and use supplemental oxygen above FL410. Should prolonged flight above FL410 be planned during single-pilot operation, it is assumed that sufficient oxygen can be carried.

A conceptual framework for additional requirements when assessing devices for use in monitoring pilots for incapacitation events is presented in Table 6-2. Note that some of the factors described in this table have known values listed in the user manual by the company that produces these devices (e.g., battery life, size/weight, etc.). Other metrics will require testing in an operational environment to properly assess (e.g., operational suitability, interoperability, etc.).

Table 6-2: Framework for Incapacitation Sensing Device Requirements

Evaluation Factor	Defining Characteristics
Battery Life	Devices not powered by the aircraft must exceed the greatest expected flight operation duration, including preflight prep, takeoff, landing, and taxiing.
Measurement Range	The device must be able to measure its associated signal (e.g., posture, cardiac waveform) in a range that is relevant for detecting incapacitation.
Wearability or Usability	Wearable monitors must not interfere with a pilot's required flight equipment, and any mounted devices must not interfere with the pilot's ability to operate the aircraft (e.g., no vision obstruction).
Size and Weight	Devices should be as small and lightweight as possible to reduce potential burden or interference with the operations in the cabin. **Maximum size and weight should be provided as a part of key system attributes and system requirements.**
Signal Latency	The delay in the measurement and analysis on incapacitation signals must comply with aircraft response safety requirements, and response time key performance attributes and system requirements should be defined by stakeholders. **Maximum signal latency should be provided as a part of key system attributes and system requirements.**
Signal Accuracy	The signal that a device generates must be accurate and precise enough to allow for near real-time analysis of incapacitation. **Accuracy tolerance, including allowable false positive rate, should be provided as a part of key system attributes and system requirements.**
Device Reliability	The device must have a low failure rate.
Maintainability	Devices must have a low mean time to repair by the company that provides the device or by the operators of the device.
Availability	The device must be mission ready a large percentage of the time. The device must be able to be purchased at a reasonable cost to support broad use across aircraft.
Operational Suitability	The device must be tested and able to accurately operate within flight environment specifications/requirements (e.g., shock and vibration resistance, varying barometric pressure, electromagnetic interference, altitude, G-forces, temperature, etc.).
Security	The device must comply with FAA cyber security requirements and must not pose a risk of personally identifiable information violations.
Interoperability	The device must be able to interface/integrate with flight deck technology as needed.
Safety Factor	Safety factors provide a tolerance to failure and help ensure the device does not introduce any unwanted hazards on the flight deck (e.g., interference with avionics signals or standard operations).

6.2 Develop Framework for Special Issuances in the Context of Incapacitation Sensing Devices

The concern over pilot incapacitation due to preexisting medical conditions may require reexamination as evolving monitoring and automation technologies continue to evolve. The impact on requirements for advanced avionics and ground systems capabilities may make the difference between being able to field unaugmented long-haul operations within today's fleet and waiting several decades for all-new type designs to incorporate a more stringent set of requirements. There appears to be some trade space between maximizing the amount of rest opportunity afforded each pilot and minimizing the duration of exposure to an incapacitation event while only one pilot is on the flight deck. Therefore, there is the potential to consider the level of automation and pilot monitoring in an aircraft when considering special issuances for aviators with otherwise disqualifying medical conditions. A conceptual framework for this is presented in Table 6-3.

Table 6-3: Notional Framework for Evaluating Special Issuances for Medical Conditions

Condition	Predicted Probability of Event	Certificate	Pilot Monitoring Requirement	Aircraft Autonomous Capability Requirement
Diabetes Requiring Hypoglycemic Medication	<x%	Third-Class	Basic incapacitation; blood glucose	Basic autopilot; remote-controlled landing
Angina Pectoris, Stable	<x%	Second-Class	Basic incapacitation; ST-segment detection	Basic autopilot; automated emergency landing
…	…	…	…	…

6.3 Begin Researching Methods for Integrating Individual Incapacitation Sensors

Expanding on the information presented within this report, MITRE CAASD recommends the following:

- Assess potential algorithms incorporating physiological monitoring signals that detect pilot awareness and incapacitation.
    - Evaluate algorithm performance using factors such as receiver operating characteristic curves, noise, and threshold selection.
    - Evaluate the performance of models that combine multiple monitoring devices.
- Conduct laboratory testing of physiological monitoring systems to assess usability and acceptance.
- Conduct statistical and simulation modeling to estimate expected risk reductions of pilot health monitoring in reference missions.

Later, more complex work would build upon this and could involve:

- flight deck testing of physiological monitoring systems for accuracy in an aviation environment
- facilitating community and industry engagement to help fill critical knowledge gaps and encourage collaboration among populations with a similar problem space (e.g., heavy equipment operators)

7 Summary

Advances in sensing and autonomy have the potential to increase aviation safety and enable reduced crew operations or allow for increased inclusivity of pilots with some medical conditions or medical risks. For example, organizations are considering strategies to increase the retirement age for pilots and/or reduce crew while maintaining or enhancing safety. In anticipation of this, this document:

- describes a framework for evaluating degrees of pilot incapacitation using representative incapacitation events, as well as monitoring devices that could be leveraged to detect these incapacitation events and trigger automation to assume aircraft control,
- presents a rubric and supporting analyses to address the requirements for monitoring technologies,
- provides an inventory and assessment of current potential pilot monitoring solutions, and
- establishes a conceptual framework where special issuances could be granted to applicants who do not meet medical standards as incapacitation detection and automation technology mature.

Furthermore, the potential exists to adapt technologies developed for other industries to assist in the detection and prediction of pilot incapacitation events. For example, several monitors and sensors assist anesthesia providers in determining if a patient is unconscious, which can be considered a type of incapacitation. Additionally, sensors used in the trucking industry to detect driver drowsiness could be modified for aviation use. Utilizing preexisting technologies from other areas could significantly truncate the timeline to deploying these monitoring technologies in a flight deck, as they have already been validated and are in use at some level outside of an aviation environment.

A suite of multiple sensors would likely be desirable to maximize the modes of incapacitation that are covered, and the sensors that make up this suite should encumber the pilot as little as possible. As technology develops further, it may be possible to execute full incapacitation monitoring with fewer sensors, either due to the increased sophistication of the sensors themselves or the development of algorithms that require fewer sensing modalities to detect the various incapacitation modes. Additional baselining could be performed on a per-pilot basis to maximize the accuracy of incapacitation detection and, based on the pilot's health, minimize the number of physiological sensors required. However, advances in these technologies must be monitored to ensure their suitability for a flight deck environment, as few sensors have been designed and tested for commercial aviation. As more sensors are validated in a flight deck setting, the sensor suite and its communication with the aircraft may change, and caution should be used such that no incapacitation signals are lost from one generation of technology to the next.

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Appendix A Detailed Use Case Scenarios

The following detailed use cases expand on the previously defined Use Case 1 to help support future considerations of sensing requirements. Figure A-1 presents an operational view for pilot health monitoring focusing on the flow of information in the event of an incapacitation. The view assumes the aircraft is operating in cruise with one pilot on the flight deck and the other resting. A variety of sensors feed information about the physical state of the pilot on the flight deck to an incapacitation detection algorithm. There is also a means for the pilot to self-declare an incapacitation. Upon detection of the incapacitation, automation recalls the resting pilot and notifies the operator and the controlling ATC authority. The resting pilot returns to the flight deck takes control of the aircraft, and provides updates as needed to the operator and ATC. Optionally, it may be necessary to detect an incapacitation to trigger a notification to the auto-flight systems to assume a specialized mode of control until the resting pilot returns to the flight deck. Further study should examine the need for this based on the objective of assuring an acceptable level of safety.

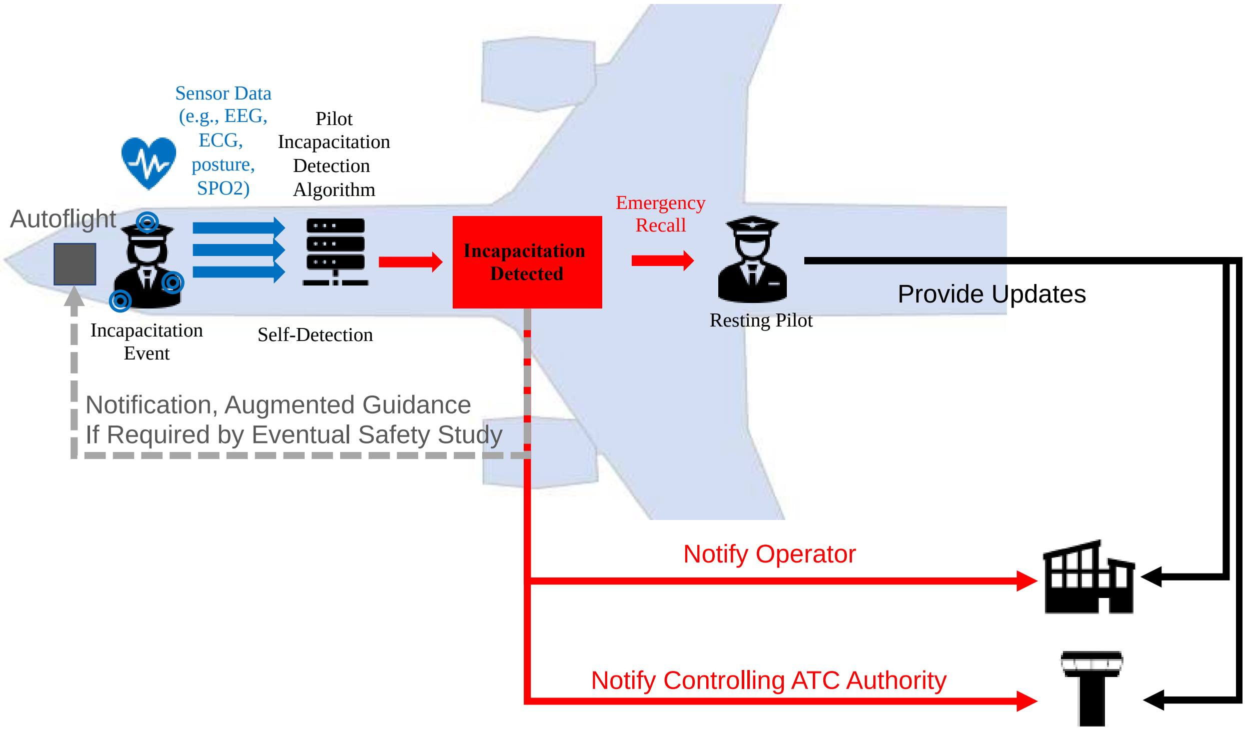

Figure A-1: OV-1 for Pilot Health Monitoring in Long-Haul Operations Use Case

The cruise phase of flight of a long-haul 14 CFR Part 121 operation is generally characterized by low workload, even when dealing with minor challenges, such as deviations around severe weather. However, there are more serious non-normal situations that can occur and raise the workload significantly, such that, given today's state of technology, the assistance of a second pilot might be considered desirable. Among those might be rapid or explosive decompression, engine fire or failure, and unreliable airspeed indications, to name a few. Crew procedures for these types of occurrences generally rely on the combined efforts of two crewmembers to ensure that irreversible or critical actions, such as engine shutdowns or the discharging of fire extinguishing agents, are handled accurately and promptly. In addition, the inadvertent penetration of severe weather or operating conditions, such as clear air turbulence or volcanic ash, can also lead to an increased workload. In this use case, a single pilot would have to be able to address non-normal scenarios without the assistance of another pilot on the flight deck. The nature of any additional assistance that may be needed is being studied. For example, using a head-worn display to present emergency procedures to pilots conducting single-pilot operations was studied (Alvarez & Rodriguez, 2021). However, pilots can and do leave the flight deck for brief periods even in today's operations; the aviation industry is at least tacitly willing to accept the risk that a single pilot may have to cope with the onset of a serious problem without assistance from the other pilot.

Many inflight emergencies require an initial period of stabilization following the onset of the emergency. This period may be needed to stabilize or alter the aircraft's flight path, secure damaged systems, activate backup systems, extinguish fires, don oxygen masks or protective breathing equipment, make an initial set of decisions, declare an emergency with ATC and/or surrounding air traffic, or any combination of these. Similarly, sometime will be needed to recall a resting pilot to the flight deck and have them overcome any sleep inertia. Depending on the nature of any emergency that may be in progress, the return to the flight deck may be complicated by reduced cabin air pressure, airframe vibration, turbulence, and/or smoke or fire. The following sections provide detailed examinations of several scenarios involving incapacitation and/or serious systems malfunctions.

Pilot Requirements and Flight Time Limitations

Air carriers certificated in the United States and conducting operations under 14 Code of Federal Regulations (CFR) Part 121, require a minimum of two pilots for every flight (Composition of flight crew, 1996). Pilots are required to remain at their duty stations unless their absence is necessary for the performance of their duties, for physiological needs, or when taking a rest period and relief is provided (Flight crewmembers at controls, 2013). Commuter and on-demand (charter) air carriers certificated in the United States and conducting operations under 14 CFR Part 135, require a second-in-command for aircraft that provide seating for 10 or more passengers (Composition of flight crew, 2018) or aircraft operating under Instrument Flight Rules (IFR) (Second in command required under IFR, 1997). However, Part 135 operations can be conducted by a single pilot under IFR using aircraft with fewer than 10 passenger seats if an approved autopilot is available (Exception to second in command requirement: Approval for the use of autopilot system, 1995).

For operations under 14 CFR Part 121, the length of the flight when the operation is conducted with the minimum required flight crew (generally, two pilots) is limited to eight or nine hours, depending on the relationship between the start time of the operation and the crew member's acclimated time zone. Longer flight times are allowed if augmented crews are used: 13 hours for a three-pilot flight crew, 17 hours for a four-pilot flight crew (Flight time limitation, 2013). Additionally, 14 CFR Part 117 defines the notion of a flight duty period, which begins when the pilot reports for duty and ends after the last flight of that shift. The flight duty period thus includes the pilot's preflight activities and the flight time and time between flights if there is more than one flight. Flight duty periods as long as 19 hours are permissible under certain circumstances.

When augmented crews are used, increased flight times are predicated upon providing adequate rest opportunities and facilities so that each pilot can rest for part of the total flight time. The distribution of in-flight rest is not entirely regulated, instead left to operator policy and/or pilot discretion. A typical schedule goal might be to ensure an equitable distribution of in-flight rest among the pilots onboard. Some regulatory constraints do exist, however. The pilot acting as the PF must be allowed to rest for two consecutive hours during the second half of the flight duty period. Additionally, the pilot who will be acting as the pilot monitoring (PM) must be allowed to rest for 90 consecutive minutes (Flight time limitation, 2013).

Figure A-2 illustrates a typical scenario. The flight is scheduled for 10 hours of flight time. Because the pilots report 90 minutes before scheduled pushback (gate departure), the entire flight duty period is 11.5 hours. The flight is operated by three pilots: captain, first officer, and international relief officer (IRO). All three pilots are on the flight deck during departure, taxi, takeoff, and climb. At the end of the climb or beginning of cruise, the IRO leaves the flight deck for a break of two hours and 30 minutes. When the IRO returns, the pilot planning to act as PM during landing provides a position relief briefing to the IRO. The briefing and associated activities might take 15 minutes to conclude, whereupon the PM leaves the flight deck for a break of two hours and fifteen minutes. The pilot planning to act as PF during landing takes the last break (two hours and 30 minutes). Thus, the PM receives more than the required 90 consecutive minutes of rest, and the PF receives more than the 120 consecutive minutes of rest required in the second half of the flight duty period. All three pilots are on the flight deck and fully briefed for the final hour of the operation.

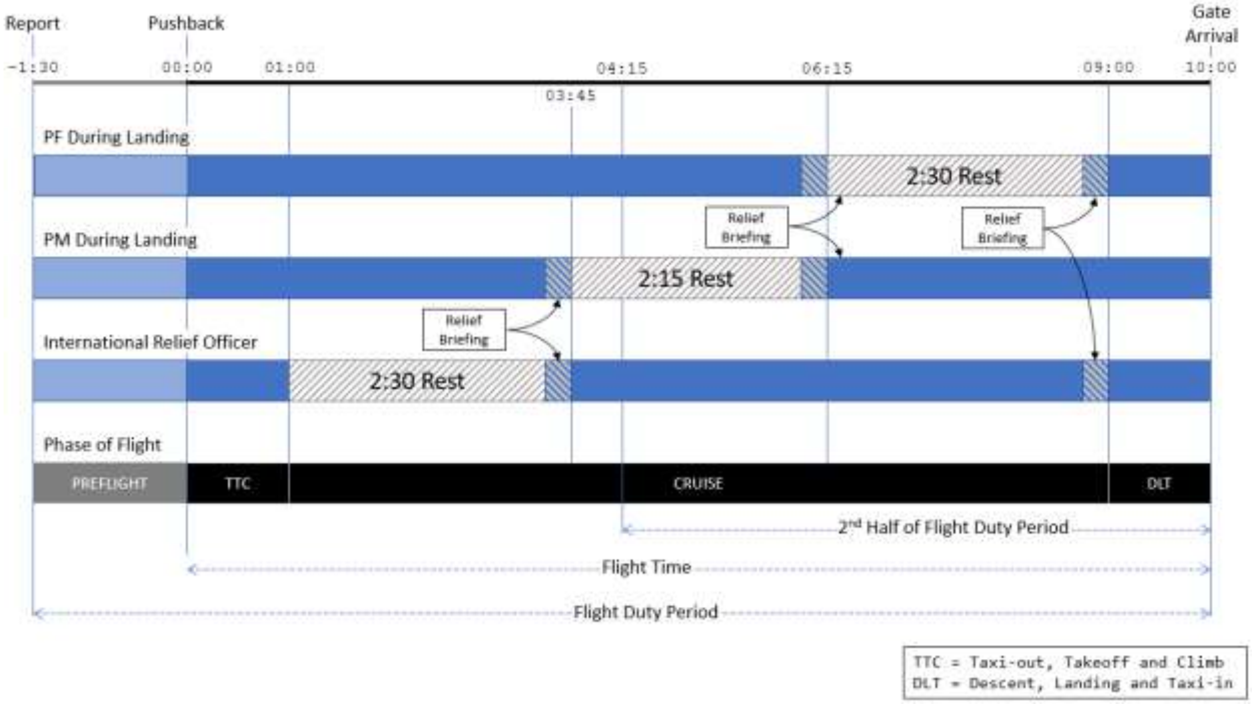

Figure A-2: Typical Distribution of Inflight Rest during a 10-Hour Flight with One International Relief Officer

These flight duration considerations and transitions between pilots will affect the requirements for real-time detection of incapacitation (e.g., battery life, allowable sleep).

Long-Haul Operations Use Case

This use case describes the use of physiological monitoring and advanced avionics and ground systems, which are systems able to intervene and operate the aircraft to enable a reduction in the number of pilots required on long-haul flights. Depending on the duration of the flight, a reduction from three to two pilots or four to two pilots may be possible. A reduction from four to three pilots may also be considered as a first step.

The reduction in the number of pilots required per long-haul flight would be enabled by reducing the minimum number of pilots required on the flight deck at any given moment during cruise flight. This allows two pilots to be on the flight deck during ground maneuvering, departure, climb, descent, and arrival phases. These phases could be operated without difference to today's operations. During the cruise phase, however, one pilot at a time could leave the flight deck for a rest break. Roles of the PM during flight crew rest may be reallocated to the ground operator and an integrated ground/air system.

A sample scenario titled "Long Haul Operations Use Case" for a 10-hour flight is shown in Figure A-3. Both pilots are on the flight deck during departure and initial cruise. One hour into the flight, the pilot designated to be the PM during landing leaves the flight deck for a rest break of one hour, 45 minutes. After the PM returns, both pilots are on the flight deck for a brief period to accomplish a position relief briefing and an orderly transfer of command. To simplify the discussion, we assume that the returning pilot has recovered from any sleep inertia before returning. Then the pilot designated to be the PF during landing leaves the flight deck for a break of one hour, 30 minutes. The PM and PF continue to alternate breaks, with the PF receiving another break of one hour, 45 minutes and the PF receiving the final break, lasting two hours. In this manner, both pilots experience fewer than eight hours of flight time with duties on the flight deck, and both pilots receive well over the minimum amount of rest required under current regulations; the PF receives the required two hours of consecutive rest in the second half of the flight duty period, and the PM receives more than 90 minutes consecutive rest.

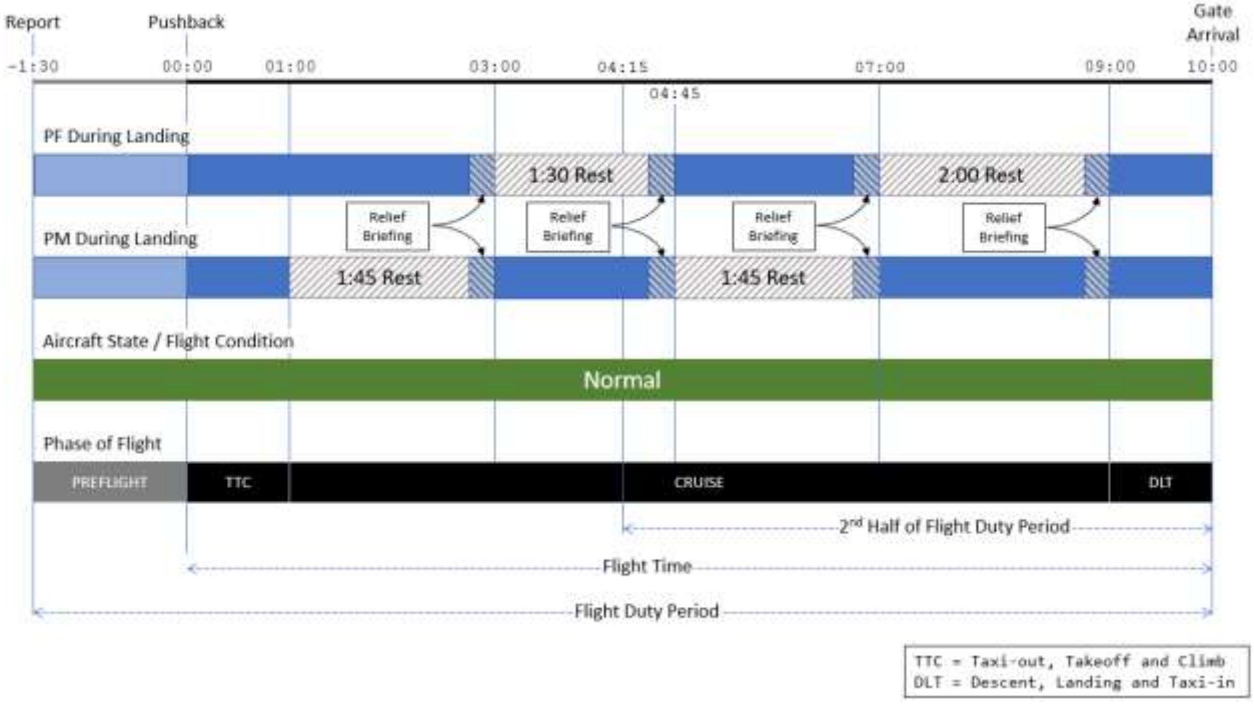

Figure A-3: Long Haul Operations Use Case with Unaugmented Crew Rest for a 10-Hour Flight

During the rest breaks, the aircraft is operated by a single pilot on the flight deck. The pilot is assisted by enhanced technology in performing routine and non-routine duties. Additional technology can detect and respond to pilot incapacitation.

Alternative Unaugmented Long-Haul Rest Scenario

As alternative unaugmented long-haul rest scenario is shown in Figure A-4.

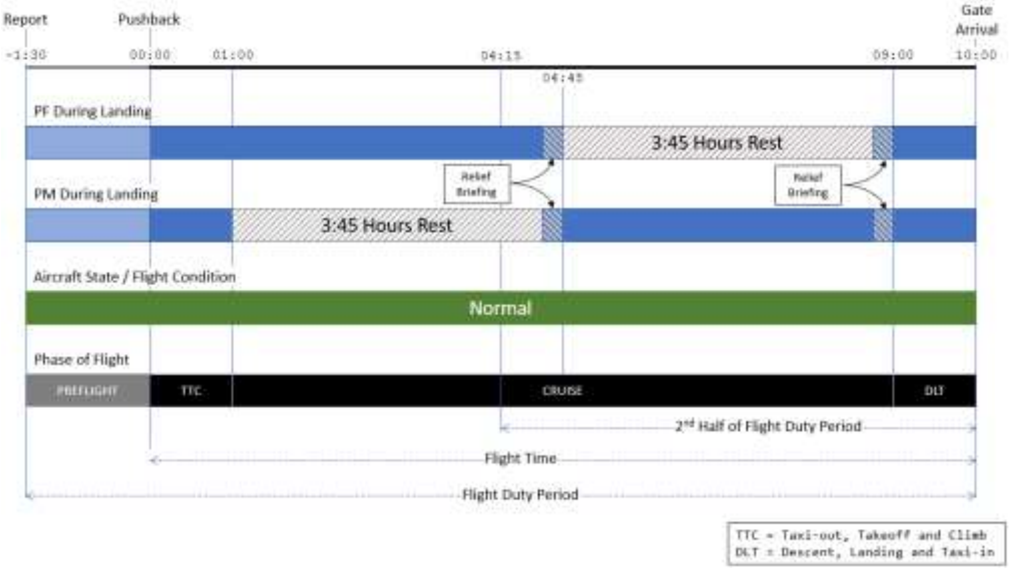

Figure A-4: Alternative Unaugmented Long-Haul Rest Scenario

Unaugmented Long-Haul Operations Use Case: Detailed Scenarios

The following scenarios in this section explore the impact of incapacitation events and systems emergencies on the nominal timeline presented in Figure A-3.

Scenario 1: Landing PF Becomes Incapacitated during Landing PM’s Second Rest Break

Figure A-5 presents the timeline for a scenario in which an incapacitation occurs late in the operation. The flight progresses nominally through the first two rest breaks. Forty-five minutes into the third rest break, the PF becomes incapacitated. The incapacitation is detected, and the PM is alerted to return to the flight deck. Upon their return, the PM may spend some time recovering from sleep inertia and becoming oriented to the flight situation. A significant difference between regaining situation awareness after returning to the flight deck after an incapacitation as compared to returning during nominal operations is that the PF may not be available to provide a briefing. For operations without flight attendants, the PM may also need some time to assist the incapacitated pilot and secure them to prevent involuntary interference with the aircraft’s controls. Although the total time needed for these tasks may not yet be fully understood, this scenario assumes 30 minutes might be a reasonable upper bound for the time it might take for the PM to become fully available to resume flying duties. This period is shown as an orange-hatched section on the timeline.

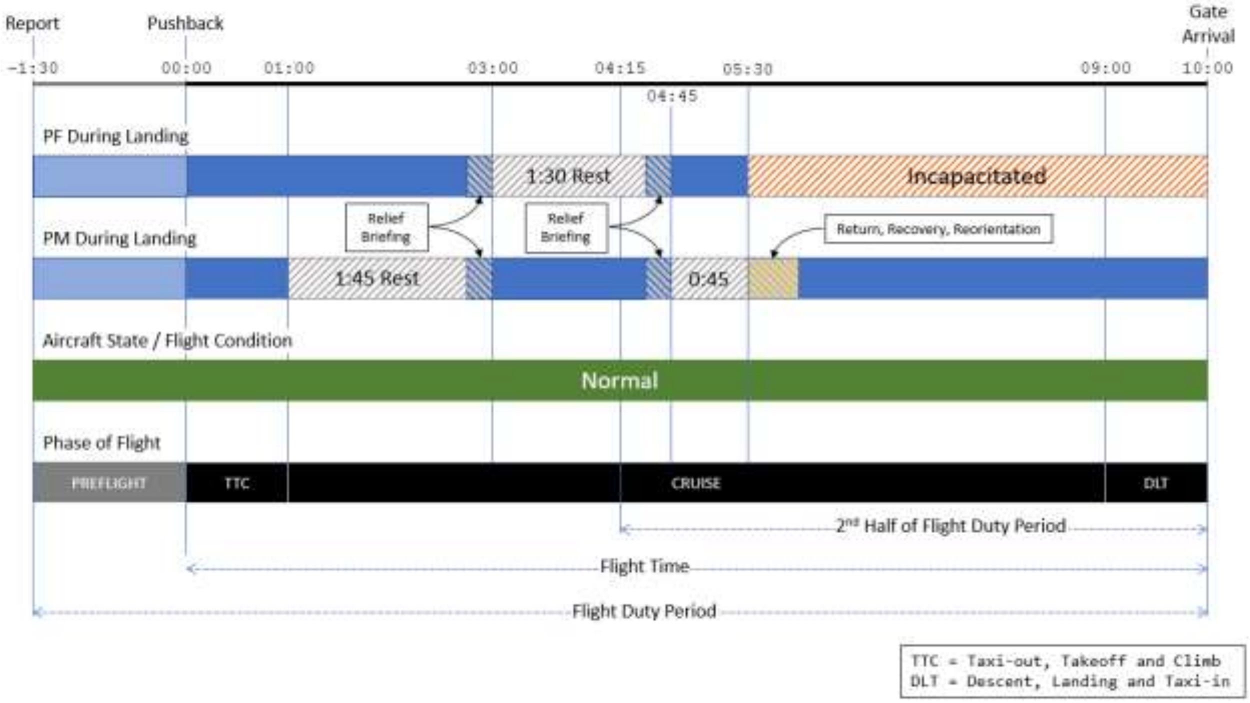

Figure A-5: Timeline: Scenario 1

If a diversion is not medically indicated, the PM may be sufficiently rested to continue the flight to its original destination, which is the scenario shown in Figure A-5. Further research may identify, however, that a diversion to a nearby suitable airfield as a matter of procedure could help mitigate the statistical risk of a second incapacitation, which would leave the flight without a qualified pilot, to an acceptable level. This scenario also highlights a potential period of increased vulnerability to the flight, as upon return to the flight deck, the PM may not be able to function at a normal performance level until having completely recovered from sleep inertia and regaining situational awareness, including fuel state and weather conditions.

Scenario 2: Landing PF Becomes Incapacitated during Landing PM’s First Rest Break

This scenario is like Scenario 1 in that an incapacitation occurs while the aircraft is in a nominal technical state. However, in this scenario, the pilot intended to act as PF during landing becomes incapacitated during the PM’s first rest break. The timeline for this scenario is shown in Figure A-6. The PF becomes incapacitated one hour into the PM’s first scheduled rest break. After being alerted, the PM returns to the flight deck. Here, too, it is assumed that the PM may require roughly 30 minutes to become fully available to fly the aircraft. During this time, it becomes apparent that the PM has not yet received sufficient rest to continue the flight to the intended destination, even if a diversion to a nearby airfield is not medically indicated.

For this reason, the PM and the flight’s dispatcher choose a suitable diversion airport. The PM obtains the requisite revised clearance from ATC and initiates the diversion. The flight arrives at the gate five hours after pushback.

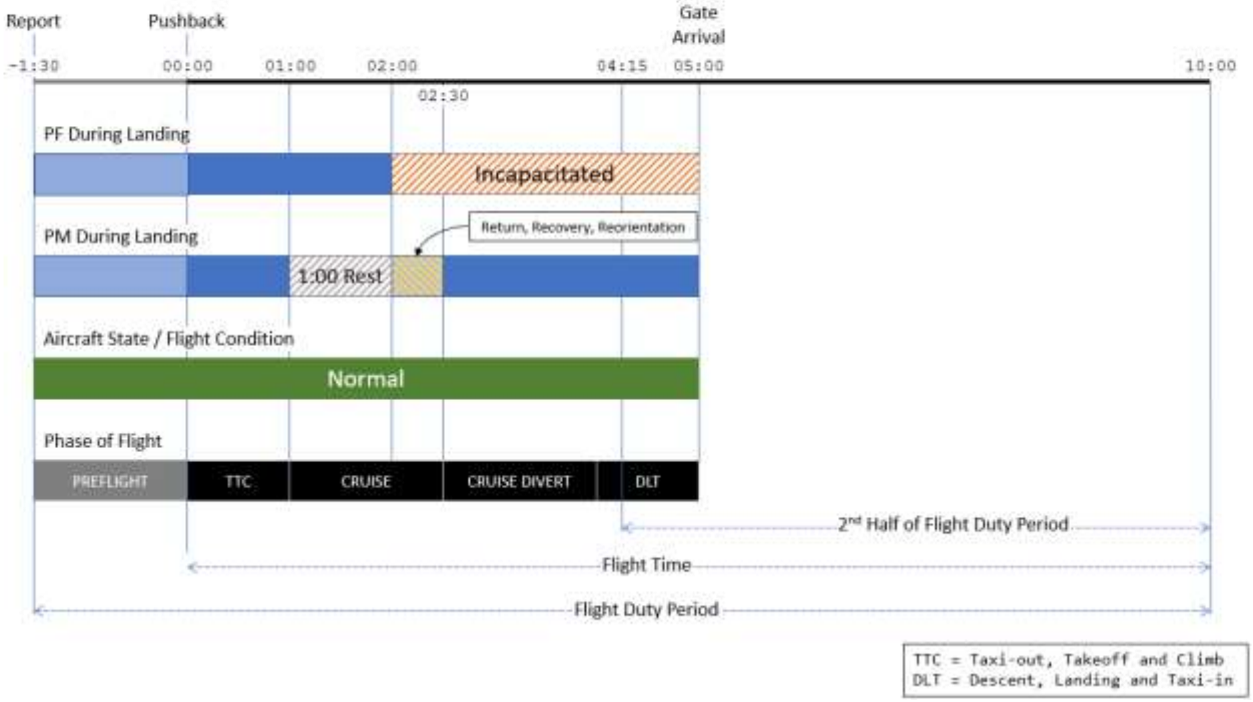

Figure A-6: Timeline: Scenario 2

Scenario 3: Engine Failure during Landing PM's First Rest Break

This scenario illustrates considerations related to recalling a resting crewmember during an emergency not related to an incapacitation event. The associated timeline is shown in Figure A-7. The pilot intended to act as PM during landing leaves the flight deck one hour into the flight for a planned one-hour, 45-minute rest break. An engine fails two hours into the flight while the PM is still resting. The pilot designated to act as PF during the landing performs the necessary tasks to secure the failed engine and effect the necessary initial changes to the aircraft's flight path, such as departing the oceanic track in the prescribed manner and initiating a descent. In this scenario, these tasks are assumed to require 15 minutes. Upon their completion, the PF recalls the PM to the flight deck. The PM will require some time to recover from sleep inertia and to become oriented to the situation. While the PM is recovering, the PF makes further progress with the emergency procedure and works with the flight's dispatcher and ATC to identify the nearest suitable airport. When feasible, the crew initiates the diversion. The flight parks at the diversion airport five hours after pushback.

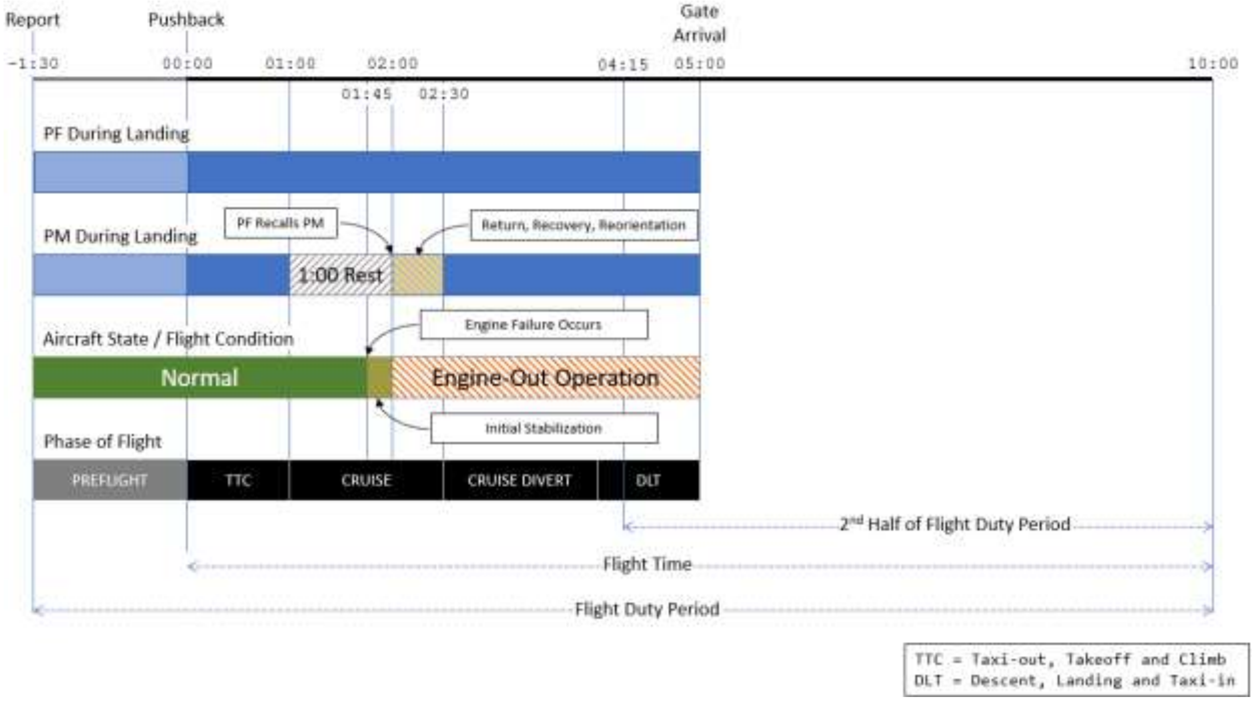

Figure A-7: Timeline: Scenario 3

Scenario 4: Engine Failure before Incapacitation Event

This scenario is the first of three examining the possibility of a serious systems malfunction and an incapacitation event occurring on the same flight. The timeline for this scenario is presented in Figure A-8. The flight progresses in this scenario as it does in Scenario 3 up to three hours into the flight. The engine failure has occurred, emergency procedures have largely been completed, and the diversion is underway. Both pilots are on the flight deck. Three hours into the flight, the pilot intended to act as PF during landing becomes incapacitated. This situation would be no different from a current-day operation and, therefore, subject to all the same presumably acceptable risks. The PM maintains control of the aircraft and aids the PF as the workload allows. The flight parks five hours after pushback at the diversionary airport.

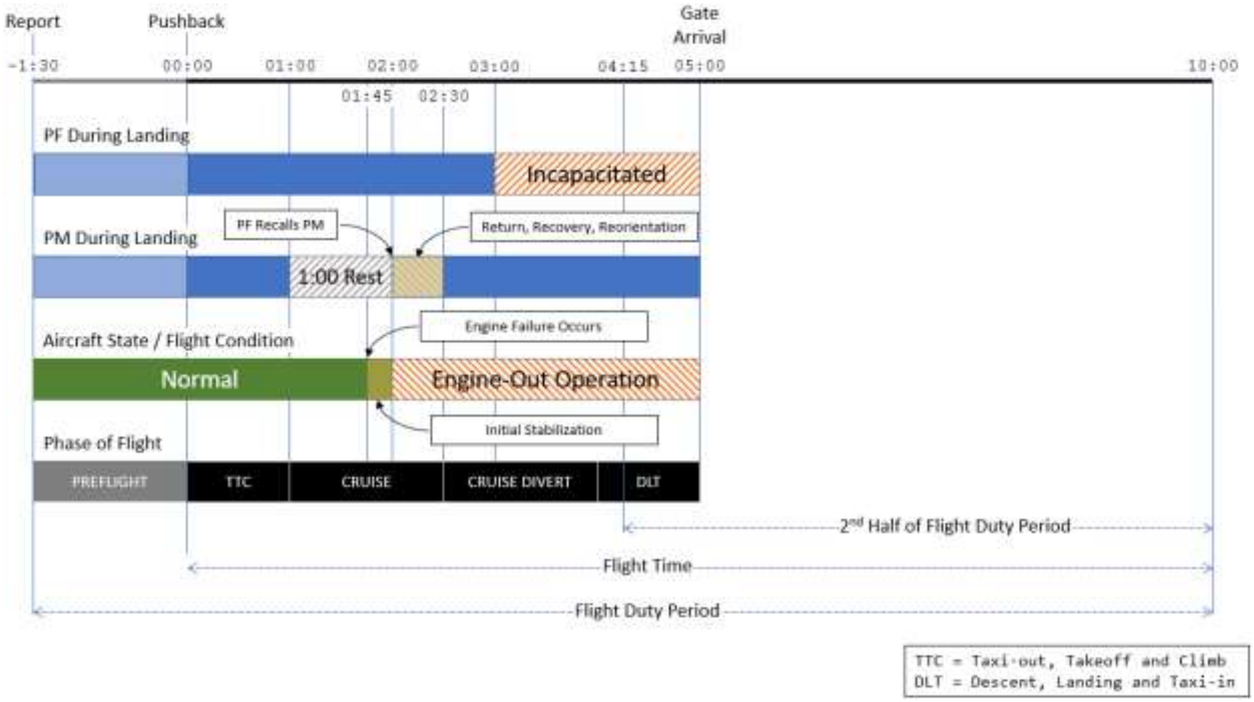

Figure A-8: Timeline: Scenario 4

Scenario 5: Incapacitation Event before Engine Failure

This scenario reverses the order of the non-nominal events presented in Scenario 4. Here, the incapacitation onset precedes the engine failure's onset. Figure A-9 presents the timeline for this scenario. Two hours into the flight, automation detects incapacitation of the pilot designated to be the PF during landing and recalls the pilot designated to the PM during landing to the flight deck. The PM returns and becomes fully reoriented to the situation within 30 minutes when a diversion is initiated. An engine fails fifteen minutes later (at one hour, 45 minutes into the flight). The PM secures the engine and continues the flight to the diversionary airport.

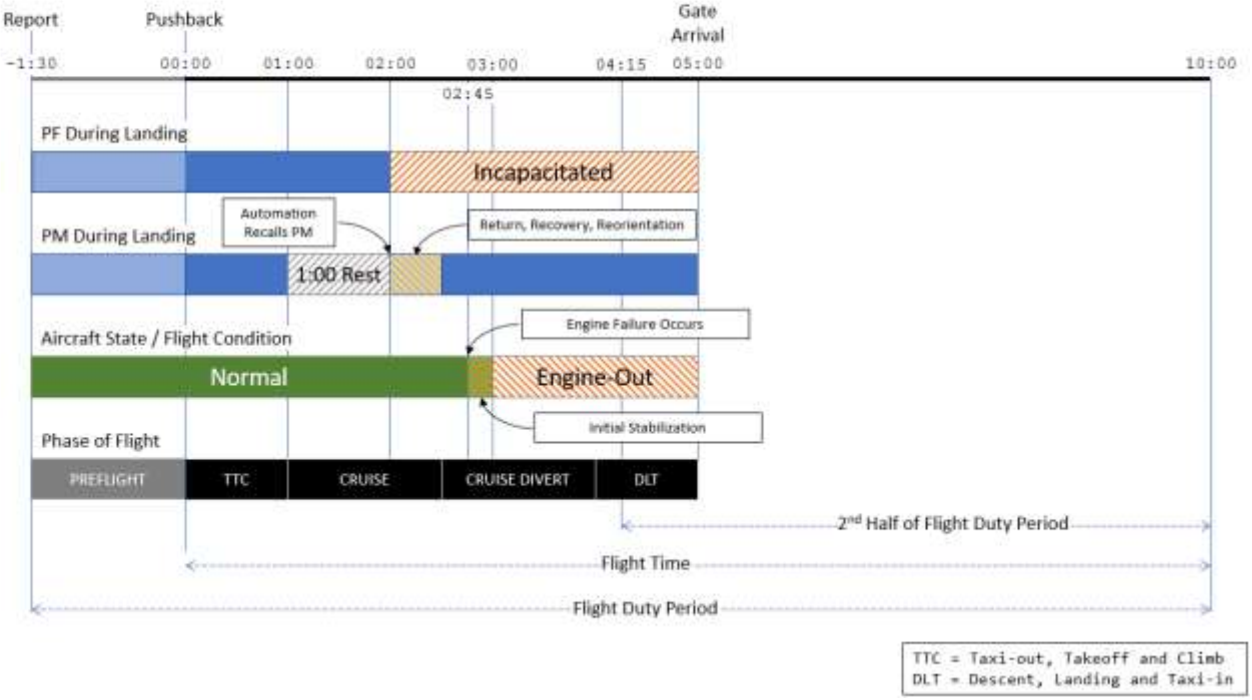

Figure A-9: Timeline: Scenario 5

Scenario 6: Engine Failure during Return, Recovery, and Reorientation

This scenario also describes a flight that suffers both an incapacitation event and a serious systems malfunction requiring immediate action. In contrast to Scenarios 4 and 5, however, the onsets of each of these events occur within a short enough time of each other such that there is no fully alert crewmember available when the engine fails to carry out tasks related to the initial stabilization of the emergency condition. The timeline for this scenario is shown in Figure A-10. The pilot designated as the PF during landing becomes incapacitated while the other pilot is resting. Automation detects the incapacitation and recalls the PM. However, while the PM is still recovering from sleep inertia, an engine fails. At this point, the flight might experience its greatest vulnerability in this scenario and when compared to the other scenarios presented so far. It is unclear what level of performance can be assumed of the PM in this instance. However, the scenario assumes that the PM does eventually secure the failed engine and initiate a diversion to the nearest suitable airport.

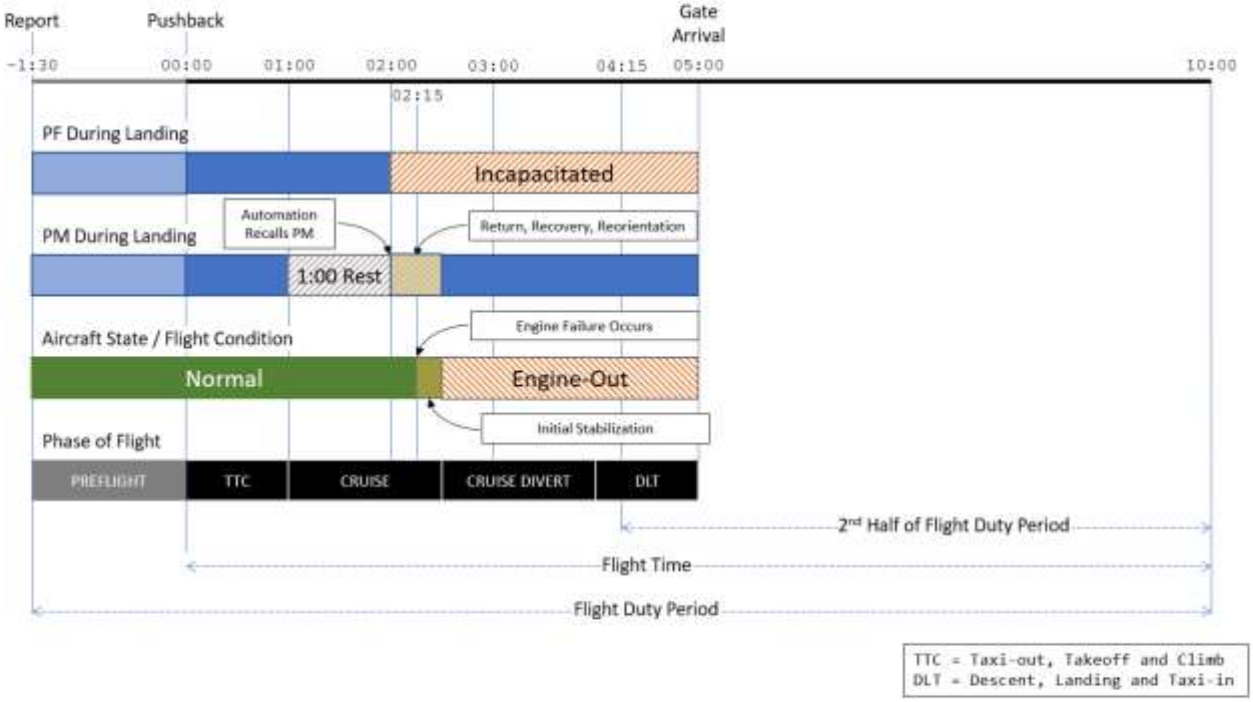

Figure A-10: Timeline: Scenario 6

Appendix B Abbreviations and Acronyms

Term	Definition
AAM	Office of Aerospace Medicine
ATC	Air Traffic Control
AUC	Area under the curve
CFR	Code of Federal Regulations
DLT	Descent, landing, and taxi-in
ECG	Electrocardiogram
EEG	Electroencephalography
FAA	Federal Aviation Administration
FDA	Food and Drug Administration
HR	Heart rate
IFR	Instrument Flight Rules
IMU	Inertial measurement unit
IRO	International Relief Officer
MCP	Mode Control Panel
NAVAIR	Naval Air Systems Command
PF	Pilot flying
PM	Pilot monitoring
PPG	Photoplethysmography
PSU	Pennsylvania State University
RR	Respiratory rate
SEH	Simple Electronic Hardware
SOP	Standard operating procedure
SpO_2	Blood oxygen saturation