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# Summary Final Report for Unmanned Aircraft Systems in Air Carrier Operations: UAS Operator Fatigue

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**Summary Final Report**

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16. Abstract

There is a rapidly increasing interest in the use of unmanned aircraft systems (UAS) for commercial operations. Title 14 of the Code of Federal Aviation Regulation (14 CFR) Part 107 describes maximum weight limits for small UAS (sUAS) and operational permissions. This regulation does not allow for sUAS in air carrier operations. UAS exceeding the weight limit of 55 pounds are only permitted in civil operations if they are directly involved in military operations or authorized by the Federal Aviation Administration (FAA) with a Certificate of Authorization. Understanding fatigue, in particular how it relates to fitness for duty, is of utmost importance because the issued flight exemptions indicate that UAS operations are already occurring without policy guidance from research. This summary report complements Durham et al. (2021), which describes an extensive literature review and annotated bibliography, consolidating information on pilot/operator duty time, shift work, and fatigue research in order to assist the FAA in developing future policy and regulations concerning UAS operators in air carrier operations. Fatigue is not an issue limited only to aviation; important human factors (HF) and ergonomics considerations from other fields that may affect operator fatigue in UAS operations are included to supplement research findings from within aviation. Articles were searched using keywords associated with unmanned and air carrier operations and fatigue. Ninety-nine articles (51 literature reviews/organization guidelines, 48 empirical studies) were found discussing duty time, shift work, and fatigue in unmanned and manned operations. The literature was summarized and organized into three primary sections: Unmanned Aircraft Systems, Manned Operations, and U.S. Military Pilot Duty Time Regulations. The review found that little research specific to UAS exists that addresses topics such as duty time, shift work, and fatigue, but found other non-aviation literature that can inform aviation research in fatigue. Further, improvements to UAS definitions and classifications are necessary in preparation for the integration of UAS into the National Airspace System (NAS). Future research directions are broken into four broad areas: Physiological Performance Metrics; Operator Knowledge, Skills, Abilities (KSAs), and Training; Systems Engineering; and Fatigue Risk Mitigation. A better understanding of fatigue in these areas can help provide guidance as demand for novel UAS operations continue to increase.

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## List of Acronyms

| | |
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| **14 CFR** | Title 14 of the Code of Federal Aviation Regulations |
| **AAM** | Advanced Air Mobility |
| **ACS** | Airman Certification Standard |
| **ARC** | Aviation Rulemaking Committee |
| **ATC** | Air Traffic Control |
| **ATCS** | Air Traffic Control Specialists |
| **AWACS** | Airborne Warning and Control System |
| **BAC** | Blood Alcohol Concentration |
| **CAMI** | Civil Aerospace Medical Institute |
| **CONOPS** | Concept of Operations |
| **CPA** | Conventionally Piloted Aircraft |
| **DOT** | Department of Transportation |
| **EASA** | European Union Aviation Safety Agency |
| **ELOS** | Equivalent Level of Safety |
| **FAA** | Federal Aviation Administration |
| **FRMP** | Fatigue Risk Management Plan |
| **FRMS** | Fatigue Risk Management Systems |
| **HF** | Human Factors |
| **ICAO** | The International Civil Aviation Organization |
| **KSA** | Knowledge, Skills, and Abilities |
| **LOA** | Loss of Alertness |
| **NAS** | National Airspace System |
| **NATOPS** | Naval Air Training and Operating Procedures Standardization |
| **OED** | Operational Errors and Deviations |
| **PTSD** | Post-Traumatic Stress Disorder |
| **sUAS** | Small Unmanned Aircraft System |
| **UAS** | Unmanned Aircraft Systems |
| **UAV** | Unmanned Aerial Vehicle |
| **UTM** | UAS Traffic Management |

## Introduction

This report focuses on operator fatigue and how fatigue factors affect the performance of their assigned duties – specifically, for consideration of Unmanned Aircraft Systems (UASs) in air carrier operations. There are several definitions of fatigue pertaining to the condition most likely experienced by personnel in the aviation industry. Here, fatigue is defined as a state of reduced readiness for duty (e.g., reduced mental alertness and physical ability) caused by sleep loss, circadian effects, and workload. In particular, fatigue is of particular interest to aviation because it is an important factor in assessing fitness for duty. Fatigue factors consistently found in the literature include:

- Circadian Rhythms (Time of Day): alertness varies over the day with a known serious reduction between midnight and 0600.
- Sleep Debt (Acute and Cumulative): failing to achieve a full restful night of sleep and failing to do so over successive nights is known to increase fatigue.
- Continuous Hours Awake (Long Days): extended duty periods are known to result in fatigue and risk. For example, wakefulness beyond 17 hours since the last major sleep period has been found to degrade performance comparable to a 0.05% Blood Alcohol Concentration (BAC).
- Workload: reported fatigue increases as work intensity increased.

Fatigue research in general shows that predicting performance for a specific scheduled or non-scheduled operation can be challenging, particularly if fatigue is not mitigated. Although UAS air carrier operations are in their infancy, it is clear from the research literature that fatigue must be considered when developing fitness-for-duty guidelines for UAS operators. Fitness for duty requirements already exist for other operations, but not for UAS air carrier operations (c.f. Title 14 of the Code of Federal Aviation Regulations [14 CFR] Parts 121, 119, 117, 135). Currently, there are three companies that are conducting Part 135 package-carrying operations with unmanned aircraft through exemptions[1]:

- Wing Aviation, LLC: FAA-2018-0835 (two decisions – spring 2019 for single-pilot Part 135 and fall 2019 for a full Part 135)
- UPS Flight Forward, Inc.: FAA-2019-0628 (October 2019 decision)
- Amazon Prime Air: FAA-2019-0573. (August 2020 decision)

These waivers were provided on a case-by-case basis, without uniform guidance or regulation to mitigate risks from operator fatigue. The purpose of this report is to identify and summarize how duty time, shift work schedules, and fatigue are addressed in manned and unmanned operations, with a focus on air carrier UAS operations, in order to provide a research framework for future UAS requirements and regulations in air carrier operations. It is unknown how demands on UAS operators may differ from demands on manned operators, and how different effects of fatigue factors (e.g., circadian rhythms, sleep debt, continuous hours awake, and workload) may contribute to reduced performance and safety. This report summarizes

[1] For details, please see docket filings at http://www.regulations.gov

research identified during a focused literature review and described in an extensive annotated bibliography (Durham et al., 2021). This work is intended to describe the current status of duty time, shift work, and fatigue research relating to UAS in air carrier operations, as well as provide a discussion on current UAS duty time regulations observed by U.S. military and maritime operations.

Primary findings of Durham et al. (2021) found that fatigue-related research within civil UAS operations is very limited. We propose a further examination of how duty schedules and operator fatigue might affect UAS operator performance and well-being to support the Federal Aviation Administration (FAA) in developing a standardized approach to training, testing, and optimizing duty period and rest requirements. Suggested research questions to further examine fatigue in UAS operations are provided here and organized into four broad categories: Physiological Performance Metrics; Operator Knowledge, Skills, Abilities (KSAs), and Training; Systems Engineering; and Fatigue Risk Mitigations. Standardizing UAS operator requirements will supports the integration of UAS into commercial air carrier operations and the National Airspace System (NAS) to improve overall safety. Additional research on duty time, shift scheduling, and fatigue in UAS operations, related to the FAA initiatives, will support ongoing FAA policy and rulemaking efforts led by the Air Transportation Division (AFS-200), and, UAS expanded operations and UAS non-segregated operations in the NAS led by the General Aviation and Commercial Division (AFS-800).

With the ever-increasing interest and prevalence of UAS in air carrier and civil operations and with regard to this particular research effort, an examination of how fatigue-related Human Factors (HF) and personal fitness for duty issues are managed and mitigated becomes highly significant. The FAA's Airman Certification Standard (ACS)[2] addresses some of these issues and is included in Table 1. Other factors not covered in the ACS, such as time of day, length of duty, shift work (i.e., rotating or changing schedules), acute fatigue, and cumulative fatigue may affect the performance of UAS operators and operational safety while conducting assigned duties. UAS flight operations, such as package/cargo delivery or air taxi, and flying over people and property all require careful operator skill and ability, but mental or cognitive alertness is also needed during each delivery operation and across the entire duty period.

Table 1
*Airman Certificate Standard for Risks of Duty Fitness*

| V. Operations | |
|---|---|
| Task: | E. Physiology |
| References: | AC 107-2; FAA-H-8083-2; FAA-H-8083-25 |
| Objective: | To determine that the applicant is knowledgeable in the physiological factors affecting remote pilot performance. |

[2] Revisions related to rulemaking are in progress in FAA-S-ACS-10A.

| | |
|---|---|
| Knowledge: | The applicant demonstrates understanding of: |
| UA.V.E.K1 | Physiological considerations and their effects on safety, such as: Dehydration and heatstroke. |
| UA.V.E.K2 | Drug and alcohol use. |
| UA.V.E.K3 | Prescription and over-the-counter medication. |
| UA.V.E.K4 | Hyperventilation. |
| UA.V.E.K5 | Stress and fatigue. |
| UA.V.E.K6 | Factors affecting vision. |
| UA.V.E.K7 | Fitness for flight. |

## Methods

All references from the literature search were collected from the PsychINFO, Google Scholar, and FAA Library databases using the following 30 keywords/phrases:

- Air Carrier Duty and Rest Requirements
- Air Carrier Fitness Requirements
- Air Carrier Staffing Requirements
- Air Carrier Testing Requirements
- Air Carrier Training Requirements
- Drone
- Duty and Rest Requirements
- Exhaustion
- Fatigue
- Operational Risk
- Operator Fatigue
- Remote Operator
- Remote Operator Fatigue
- Remote Pilot
- Remote Pilot Certification Requirements
- Remote Pilot Fatigue
- Remote Pilot Operation
- Remote Pilot Training
- Risk
- UAS Air Carrier Operations
- UAS Air Carrier Remote Pilot and Crew Requirements
- UAS into the NAS
- UAS Operations
- UAS Operator Certification
- UAS Regulation
- UAS Rulemaking
- UAS Standards
- Unmanned
- Unmanned Operations
- Unmanned Transportation

Following a review of the additional articles, annotations for specific articles were included in Durham et al. (2021). Ninety-nine articles (including 51 review/organization/government guidelines and documents, and 48 empirical studies) discussing shift work and fatigue in unmanned and manned operations were included and annotated. The annotated bibliography was developed with three primary headings: Unmanned Aircraft Systems, Manned Operations, and U.S. Military Pilot Duty Time Regulations. Relevant subheadings were included within each of the three sections by topic. Rather than duplicating Durham et al. (2021) for this report, an expansion of text within each individual subheading was made to summarize the reference content and provide a description of lessons learned from the information contained in the various articles and documents cited in the literature review and annotated bibliography.

## Summary of the Research Literature

### Unmanned Aircraft Systems

#### *Shift Work, Fatigue, and Fatigue Risk Management*

Research in this area is primarily related to military UAS operations, though relevant due to shared concerns regarding shiftwork, fatigue, and risk management. Human error, regulation violations, and accidents are all found to rise with increased levels of fatigue experienced by operators (i.e., pilots). Manning et al. (2004) reviewed military piloted Class A accidents between 1974 and 1992 and found that fatigue was a contributing factor (≤ 25% of reviewed accidents), and that during 1995-2003, 56 UAS accidents were reported. Human error accounted for nearly 20% of those UAS accidents with fatigue as the most likely underlying factor in judgment errors. Factors such as lengthy duty times and long periods of continued workload at the UAS workstation were found to contribute to fatigue (Scheiman et al., 2018), especially under conditions of high task saturation (Paullin et al., 2011). In addition, episodes of sleep loss or fragmented sleep have been found to contribute to higher fatigue risk and performance impairment (Thompson et al., 2006). This is particularly well-documented when rotating shiftwork schedules are in play (Van Camp, 2009). Conducting multiple operations also becomes increasingly more difficult when operators are working shifts opposite of their normal daytime cycle (i.e., night shifts) or if the operator is fatigued in general (Center for Robot-Assisted Search and Rescue, 2019).

It has also been reported that a proportion of operators are arriving and leaving work fatigued, increasing risk both on and off duty (Scheiman et al., 2018). Inadequate rest between shift assignments has been identified as a probable contributor to fatigue with cumulative sleep debt resulting in lower performance, becoming more pronounced at the end of a shift, and worsening over a workweek. Tvaryanas et al. (2008) examined shift scheduling in sustained operations and its impact on decreased mood and cognitive performance across different shift and rotation schedules. In a three-shift system, fatigue effects were found to be more pronounced on day and night shifts compared to evening shifts; fatigue was also found to be greater on rapid versus slow rotating shift schedules. These results suggested that increased fatigue was due to poor and ineffective scheduling and inadequate opportunities for recovery sleep (Tvaryanas et al., 2008; see also Tvaryanas & MacPherson, 2009). Thompson et al. (2006) further supported this conclusion, suggesting that fatigue issues might have been due to inadequate opportunities for restorative recovery sleep, problems associated with adjusting circadian rhythms during rotating work schedules, and a resultant diminished sleep quality. Regardless, alternative staffing-to-cost analysis might be considered important when developing more effective scheduling of UAS operations. Norton (2016) described three classification requirements to assist in staffing UAS operators/pilots including: system complexity, assumed risk, and the operational environment. It is important to remember that fatigue in human operators affects fitness for duty, and the ability for human operators to meet duty requirements affects the UAS and the whole NAS.

Computational models may help provide insight into how fatigue affects human performance in UAS operations. Crandall et al. (2008) used intensive computational models to understand how different operations affect the pilots' performance during their duty assignments and found that modeling may provide better predictive recommendations for reducing difficult operations when metrics adequately describe limits of both the human and aircraft as a whole UAS system. Some portions of UAS operations are automated, thereby reducing the workload of an operator and improving responses to non-routine events, such as recalculating flight plans or performing evasive maneuvers. This would certainly lessen the burden of operating multiple Unmanned Aerial Vehicles (UAVs).

Occupational burnout – commonly defined in the literature as a combination of emotional exhaustion, cynicism (sense of indifference), and personal efficacy (sense of accomplishment) – is related to fatigue. Active duty military UAS operators attributed shift work, shift changes, and hours worked as contributing to burnout levels (Ouma et al., 2011). Typical impacts of burnout ranged from an impaired ability to complete tasks assigned to difficulty interpersonally relating to other pilots. These burnout factors must be considered in conjunction with fatigue factors when determining fitness for duty among UAS air carrier operators.

***Military and Maritime***

Although the U.S. military has invested resources into research and development of UASs since World War I ("Kettering Bug"; Smithsonian Magazine, 2013), the first widespread use of UASs in wartime operations occurred during the Gulf War in 1991, with increasing developments in military applications taking place quickly after this (Gupta et al., 2013). Research into military UAS operations and the human operator has largely focused on operator mental or emotional well-being, including the occurrence of Post-Traumatic Stress Disorder (PTSD) – a condition of prolonged exposure to high cortisol levels following a traumatic event – which can affect fatigue factors. This is not surprising, as military UAS operators are exposed to visual stimuli and work conditions that may put them at risk for relatively poorer mental well-being. Specifically, UAS operators "commute" to a war zone, suggesting that they are subjected to family stressors at home in addition to combat stress due to the unique work environment (Armour & Ross, 2017).

However, research suggests that the prevalence for PTSD among military UAS operators is actually lower than among returning military personnel after deployment (4.3% versus 10-18%, respectively; Chappelle et al., 2014a). Further, a second examination of the occurrence of PTSD among military UAS operators suggested that an even smaller percentage (~2%) of respondents reported high levels of PTSD symptomology (Chappelle et al., 2014b). Research on UAS operators in the United Kingdom also suggested low levels of PTSD, though results from other clinical assessments suggested concerns with social adjustment and hazardous or harmful drinking (Phillips et al., 2019). Factors that have been associated with a greater risk of PTSD include time on station over 24 months, working greater than 50 hours in a week, shift work, and scheduling concerns such as feeling understaffed (Armour & Ross, 2017; Chappelle et al., 2014b). Together, the results from these studies suggest that the main occupational stress factors for UAS operators may be more related to workplace and shift issues, and less to traumatic stress (Chappelle et al., 2011; Hardison, 2018).

Stressors not directly related to combat may further contribute to relatively poor well-being among military operators (Chappelle et al., 2011; Hardison, 2018), thus highlighting the importance of understanding occupational stress among UAS operators. Preliminary research on occupational stress amongst military UAS operators has identified some consistent concerns related to shift work including manning, tasking, and scheduling (Hardison, 2018); long hours, shift work, additional administrative duties, and low staff (Chappelle, 2014b); and stress/emotional exhaustion (Chappelle et al., 2011). The consequences of occupational burnout and occupational stress may include increased alcohol and tobacco use, increased use of medical services, and increased use of prescription and over-the-counter drugs (Armour & Ross, 2017). Furthermore, increased fatigue has also been associated with increased risk-taking behavior in UAS crews (Caid et al., 2016). As UAS endurance capabilities continue to increase with technological advancements, the concern with increased risk of operator fatigue and human error will continue to be a concern (Arrabito et al., 2010; Burmeister et al., 2014).

Potential countermeasures to UAS operational stress should include a balance of both policy and technological considerations. For example, schedules must account for unique operating conditions, such as the number of UASs concurrently flown or supervised by a single operator, potentially hazardous weather, and the difficulty of the task (Hoepf et al., 2015). Technology interventions may include the use of automation to potentially reduce fatigue by allowing multiple crews to operate one aircraft remotely (Burmeister et al., 2014), or by tasking the human operator as a supervisor of an automated system, rather than a traditional pilot with control of the aircraft's flight surfaces (Hoepf et al., 2015). H issues related to control station design should also be considered in determining occupational stressors. For example, the UAS operator may experience "sensory" isolation (i.e., a lack of vestibular and spatial cues) when operating a UAS, and thus a display should provide multimodal data to assist with interpreting sensory data (Hopcroft et al., 2006; Man et al., 2015; Porathe et al., 2014; Wahlström et al., 2015).

Although there are many contributing factors to UAS accidents (Oncu & Yildiz, 2014), the increasing complexity predicted for future UAS operations suggests that further research is needed to help determine and mitigate the factors that contribute to occupational stress. Future research should continue to explore the relationship between the unique operational demands imposed on UAS operators, and concomitant stress and well-being experienced by the operators. Additionally, the interaction between HF concerns with workspace design and technology advancements should be taken into account.

### *Human Factors/Ergonomics*

This subsection references an assortment of HF/ergonomics articles on topics and information relevant to design and interface issues, workload of the UAS operator, and automation. Alicia (2015) discussed a transitioning of cautionary alarms that might be presented in one sensory modality to another modality in order to counteract what that author described as a modality shifting effect. Howse (2011) provided a discussion on the knowledge, skills, abilities, and other characteristics necessary for UAS operators in the performance of their assigned duties. A literature review was conducted on UAS in military operations to create a taxonomy of information needed to control UAS and improve training. The review produced similar conclusions: cross-training and multicultural training methods were recommended for knowledge-based information exchange and trust training, informed by the operator's positive attitude (Pavlas et al., 2009; Szabolcsi, 2016). A review concentrating on UAS control station design guidelines provided examples of how the human-machine interface might be improved by applying HF guidelines, including task descriptions, display requirements, control requirements, properties of the interface, and general HF principles (Hobbs & Lyall, 2016). This review suggested that HF guidelines for the design of UAS control stations could be systematically developed with FAA guidance. Waraich et al. (2013) suggested that HF/ergonomics standards could be applied to designing and evaluating UAS ground control stations to mitigate potential human error.

Modeling is an important tool for identifying what needs to be managed and when. Coppin et al. (2009) recommended that an accurate and effective bidirectional interaction needs to exist between the human and the system for mutual understanding to occur. In another study of interactive systems between computer and human control, the use of certain psychophysiological measures were used to measure an operator's mental state as predictors of performance to improve the control of multiple UAVs (Singh et al., 2019). A multi-layer architecture using incoming data from onboard sensors to guide the UAS in an autonomous manner could be used, thereby reducing operator workload (Narayan et al., 2007). However, another article proposed a new model of human-system interaction to improve communications and assist the operator with decision-making processes (Tvaryanas, 2006). Most recommendations offered design and procedural elements to reduce workload of the operator. A comparison study was conducted with the Axon Workload Test (a modified version of the NASA-Task Load Index) as a subjective measure of workload (De La Torre et al., 2016). This study showed how mental workload correlated with landing procedures and how workload also correlated with total errors during the mission sequence. Findings suggested that self-reported workload via the Axon Workload Test might be useful in further understanding of human errors in UAS operations.

Increasing automation may allow for decreases in staffing by allowing an operator to control multiple UAVs. Using time-locked psychophysiological measures as critical input into an automated system, the human mental state might predict successful control handovers between the human and the computer (Coppin et al., 2009). Regarding other psychophysiological measures, Stern et al. (1994) reviewed the literature on eye blinks and blink rates as a possible index of fatigue. They suggested that blink rates may be linked to cognitive fatigue and found higher blink rates at the end of the testing sessions when fatigue was highest. However, it is important to note that task load can compound fatigue. Interestingly, blink rates measured in pilots and co-pilots found that the person in control of the aircraft had lower blink rates (Stern et al., 1994). These results are in line with expectations, further suggesting that blink rates could be used to assess UAS operators/pilots attention and or workload during a mission. A study designed to look into task demands and automation found that vigilance was lower when surveillance tasks were demanding, and dependence on automation decreased over time. Essentially, participants discounted automation information to reduce mental demand under increasing fatigue (Wohleber et al., 2019).

### *UAS Airworthiness Certification Categories and Regulations*

It is important that UAS airworthiness certification categories continue to be developed in such a way as to support an equivalent level of safety (ELOS) to conventionally piloted aircraft (CPA). Elements that contribute to ELOS include both UAS airworthiness certification standards and the UAS technology itself. It is generally agreed that UAS airworthiness should be determined by the potential harm caused to people and property on the ground, which takes into consideration both the region over-flown as well as the UAS system reliability (Clothier et al., 2011). This is different than categories for CPA where airworthiness is principally defined by the risk to those onboard the aircraft, without consideration for the area over-flown (Clothier et al., 2011). Further, risks associated with CPA are somewhat mitigated by the fact that the human pilot onboard can use natural senses, such as vision, to sense and avoid hazards (Cook et al., 2012; Dalamagkidis et al., 2008; Hayhurst et al., 2006). However, an adequate detect-and-avoid system for a UAS has been difficult to develop, and as such, an instrument failure may lead to an accident. The operations for UAS and CPA also differ in that CPA are usually flown in a point-to-point route, while a UAS may be used in a situation that requires the UAV to maintain a general position for hours at a time (e.g., surveillance; Dalamagkidis et al., 2008). Though military CPA operations permit orbiting for hours, such as with Airborne Warning and Control System (AWACS) and air refueling operations. Accidents involving a UAS may be deemed acceptable in order to reduce damage to property of persons, whereas a crash of a CPA is considered catastrophic (Dalamagkidis et al., 2008). Because of the differences in risks and hazards between UAS and CPA, such as likelihood, severity, duration, and expectation, it is unreasonable to apply factors and operational limitations in existing (14 CFR) regulations to UAS certification (Maddalon et al., 2013).

It has been suggested that a risk matrix may be utilized to provide a framework to structure airworthiness certification for UAS (Clothier et al., 2011; International Civil Aviation Organization [ICAO], 2019; Maddalon et al., 2013). The risk matrix should include systematic assessment, comparison, and ranking of risks associated with UAS type and operation (Clothier et al., 2011). Further, ICAO (2019) has identified needs for risk assessment, contingency plans in case of system failures or emergencies, UAS separation standards, and standards for UAS Traffic Management (UTM) service suppliers. Determining UAS operations categorized based on risk rather than quantifiable metrics, such as weight or size of the aircraft, is consistent with the views of the European Commission (2019) on UAS rules and guidance. Another consideration should be the risk of UAS collision with another aircraft, and the risk of UAS impact with people or structures on the ground (Washington et al., 2017). Strategies used for military integration of UASs into the airspace may be transferable or at least form a basis for UAS policy development (Wolf, 2013).

## Manned Operations

### *Shift Work, Fatigue, and Fatigue Risk Management*

Different workforces and respective operational strategies are used to increase alertness, augment performance, and support fatigue risk management given the known effects of shiftwork and non-optimal work schedules. A few articles report original research to identify current rest/duty schedules, fatigue risks, and specific duties and responsibilities that might be susceptible to the effects of fatigue. The development of company management plans that outline specific policies and procedures for reducing the potential effects of day-to-day operational fatigue are included.

The Airline Safety and Federal Aviation Administration Extension Act of 2010, 111-216, § 212 (b), required the FAA to prescribe requirements for the Fatigue Risk Management Plan (FRMP) for 14 CFR Part 121 air carrier operation pilots. The FRMP was instructed to include specific elements including:

1. Senior Level Management Commitment to Reducing Fatigue and Improving Flightcrew Alertness.
2. FRMP Scope and Fatigue Management Policies and Procedures.
3. Current Flight Time and Duty Period Limitations.
4. Rest Scheme Consistent with Limitations.
5. A Fatigue Reporting Policy.
6. Education and Awareness Training Program.
7. Fatigue Incident Reporting Process.
8. System for Monitoring Flightcrew Fatigue.
9. FRMP Evaluation Program (see FAA Order 8900.1 CHG 301; FAA, 2013b)

Some FAA documents suggest an empirical approach, including research to develop appropriate fatigue mitigation strategies and guide policies for providing rest opportunities. This approach is particularly important when extending operational duty periods beyond regulated limits (FAA, 2013a). Two FAA technical reports (Bryant et al., 2016; Hobbs et al., 2011) provided recommendations and best practices for aircraft maintainers and cargo/flight mechanics, and described three primary objectives of a Fatigue Risk Management System (FRMS) including: reduce fatigue, reduce or capture fatigue-related errors, and minimize the harm of errors. ICAO (2015) described three areas in their recommended approach to fatigue risk management and provided similar measures, practices, and policies as many of the other articles concerning FRMS.

Other research described current strategies for improving alertness, including various in-flight fatigue countermeasures such as cockpit lighting, in-seat napping, activity breaks, bunk sleeping, and in-flight rostering (Brown et al., 2014; Caldwell et al., 2009; Jay et al., 2015; Rudin-Brown et al., 2018). Also mentioned were pre- and post-flight fatigue countermeasures such as hypnotics used in military operations, positive sleep hygiene used by all, and non-FDA-regulated substances and devices like melatonin and bright light to manage circadian rhythm alignment or re-entrainment. Loss of Alertness (LOA) is of particular concern because it can be caused by a variety of factors. A Department of Transportation (DOT) technical report discussed the impact of LOA, described the factors contributing to it, and provided preventive and assessment measures; the report showed that most organizations address LOA by assessing fitness-for-duty, monitoring vehicle operators, providing educational interventions, and updating the working environment (Freund et al., 1995). Physiological monitoring has also been offered as a means of recognizing alertness issues and, if integrated into the human-machine interface, can greatly improve operations and reduce error (Wilson et al., 2016).

***Air Traffic Control***

Research in Air Traffic Control (ATC) can provide guidance on shift work and fatigue countermeasures in UAS air carrier operations. This subsection is included because UAS commercial operations, as currently authorized, are restricted primarily to day shift operations only. However, much of the research conducted with Air Traffic Control Specialists (ATCSs) finds that even with a 24/7 operational requirement and a three-shift scheduling system, elements of fatigue are present during early mornings and daytime operations (Cruz et al., 2002; Della Rocco & Nesthus, 2005). Differences were found in controllers' alertness and performance during 8-hour compared to 10-hour work schedules (Schroeder et al., 1995). Krishnan et al. (2014) found that particular electroencephalogram brain wave activity changed over time and suggested that mental states were correlated with a general performance decline after around 70 minutes, indicating that mental fatigue was taking place.

Restricted sleep is commonly experienced for day shift personnel and research shows that operational errors and deviations (OEDs) appear to occur at a higher frequency than during the swing and night shift operations (Della Rocco, 1999). Another study on OEDs and vigilance found that performance on detecting conflicts declined over time on tasks and across work periods (Schroeder et al., 1994). Together, these results suggested that vigilance and performance are a function of task complexity and consistent with an increased number of lapses in attention. Essentially, a controller's performance on detecting conflicts decreased with time on task across periods, but performance did improve from the first to last session. Performance of identifying altitude malfunctions remained relatively stable to time on task effects and across sessions, and detection of aircraft intruders found both improvements in performance and evidence of time on task effects (Schroeder et al., 1994). Two related articles outlined a list of work and non-work related factors affecting controller performance (Gawron et al., 2011; Nealley & Gawron, 2015). These articles pointed out that during a work schedule, the time and activities people are involved in between shifts and rotating schedules can affect sleep quality and quantity. Other non-work related factors, including individual differences (e.g., personality characteristics), age, family responsibilities, and sleep disorders (i.e., treatment compliance) were also shown to contribute to poor performance on duty. Certainly all of these factors would also pertain to UAS operators as one might expect from commonalities in reporting.

The several ICAO guidance documents for pilots and for ATC services described multiple approaches to managing fatigue relevant to UAS operations. Recommendations for predictive, proactive, and retroactive methods in identifying fatigue hazards were provided. These might include schedule guidance coming primarily from experience (e.g., evidence-based scheduling), recommended use of bio-mathematical models of fatigue, recording self-reported fatigue, regular documentation of past and present fatigue evidence, acquiring performance data (when possible), and the incorporation of existing relevant scientific data (ICAO, 2015, 2016a, 2016b). The general carry-over from these international references is in the promotion and application of fatigue risk management principles and to understand that fatigue has unique effects on individuals, is common in shiftwork, and affects health and safety (McCauley & Nesthus, 2017). Integrating FRMS programs into the operation must:

- Be scientifically data-driven;
- Continuously monitor and manage fatigue risk and hazards;
- Provide methods for measuring, mitigating, and reassessing fatigue risks;
- Include schedule assessment, data collection, and system analysis; and
- Provide fatigue mitigations that are scientifically guided.

It is important to follow-on with possible mitigations that include fatigue-smart scheduling practices, provide a means of recuperative breaks during the operation, manage as well as possible, the potential sleep disorders found commonly in our adult population, encourage development of sound personal fatigue management practices, and provide fatigue awareness and education training for operations personnel.

### ***Flight/Cabin Crewmembers and Air Medical Operations***

Consistent with other workforces, there are major challenges and concerns with managing pilot and aircrew fatigue when flying with “scheduling factors, sleep deprivation, circadian disruptions, and extended duty periods” (Caldwell, 2005). This article found decreased cognitive function and vigilance lapses in short and long-haul operations and night operations, which can disrupt the natural circadian rhythms. Moreover, Caldwell (2005) recommended some of the same methods for fatigue prevention including: fatigue awareness training and education, providing, if possible, additional sleep opportunities during duty periods, and developing fatigue-smart break and schedule management within each respective flight operations. In a relatively restricted operational field study directed by European Union Aviation Safety Agency (EASA, 2019), researchers found two elements contributing to fatigue, 1) duties of more than 10 hours during less favorable time of day, and 2) disruptive schedules, both of which referred to night flights. Again, this study's recommendations were similar to other studies and referred to the development and practice of fatigue risk management techniques, attaining adequate sleep before night operations, especially for duties over 10 hours, and generally taking advantage of all sleep opportunities to obtain sufficient sleep before any flight operation.

Consistent with EASA's (2019) study of flight periods of 10 hours or greater having an impact on performance, Goode (2003) found an increased probability of accidents with pilot's hourly duty periods greater than 10 hours. The recommendations from Goode "…suggests that establishing limits on duty time for commercial pilots would reduce risk" (2003). Flight attendants and emergency medical service personnel are shown to exhibit similar effects with increased duty time and restricted rest periods promoting greater fatigue resulting in a degradation in the performance of their respective duty requirements (Avers et al., 2009; Avers et al., 2011; Roma et al., 2010).

When the fatigue literature in civil and military pilots was reviewed, Gawron (2016) found that pilots were consistently exposed to a variety of factors associated with increased fatigue:

"1. Reduced sleep;
2. Length of duty day and time of task;
3. Long haul versus short haul;
4. Number of sectors flown during the duty day;
5. Reduced crew;
6. Time of day with early morning being associated with the most fatigue,
7. Overnight versus daytime trips; and
8. Return rather than outbound flights" (Gawron, 2016, p.16).

Gregory et al. (2010) found in a pilot fatigue survey of fatigue factors in air medical operations many of the same contributors to fatigue and suggested improved fatigue and sleep management recommendations such as attaining seven to nine hours of sleep every night, and as much as possible before night flights, and avoiding accumulated sleep debt over a trip sequence. Gregory et al. also discussed the effects of age, alcohol, and sleep disorders on reduced alertness and sleep debt. Nix et al. (2013) highlighted similar issues and recommendations in a study on pilot fatigue in helicopter emergency medical.

Samel et al. (1997) studied aircrew fatigue in long-haul operations and recommended keeping day flight operations $\leq$ 12 hours for two-pilot crews and $\leq$ 10 hours for night flight operations. Sprengart et al. (2018) found that reducing the flight deck crew size would place higher levels of workload on the pilots who remain on the flight deck, and recommended against the implementation of that concept. Strauss (2006) examined existing flight regulations and found them to be designed to prevent overworking, but concluded that existing regulations do not promote adequate sleep or sleep recovery. Strauss recommended that regulation change should include criteria for maintaining adequate sleep, better fatigue training for pilots, and measures to identify early signs of fatigue. Pilot flight time, duty time, and rest requirements in the United States were revised in 2014 and can be found in 14 CFR Parts 117, 119, and 121. This major rule change represented an approach to integrate circadian rhythm and fatigue science into the regulation for better fatigue risk management and to provide maximum limits on flight time and flight duty period, as they interact with other parts of the rule. In addition, an Aviation Rulemaking Committee (ARC; FAA, 2019) was chartered to review and develop rules and recommendations for pilot rest and duty rules under 14 CFR Part 135.

## U.S. Military Pilot Duty Time Regulations

U.S. military policies for flight scheduling standards and crew rest requirements for manned flight operations also apply to unmanned flight operations and fatigue risk management. In general, the restrictions for duration of a flight operation depend on the number of pilots (i.e., single pilot versus multiple pilot operation), with a consideration for the total amount of flight hours in a given time period – typically one week. Further, most branches of the military have guidelines on the amount of rest required between shifts. Here, we provide a brief overview of current policies for the U.S. Air Force, U.S. Army, U.S. Navy and Marine Corps, and U.S. Coast Guard. A more detailed description of military duty and crew rest requirements for unmanned operations as related to operator fatigue can be found in Durham et al. (2021).

### *Air Force*

U.S. Air Force General Flight Rules dictate that single control station UAS do not exceed 12 hours, and dual control station UAS do not exceed 16 hours (U.S. Department of the Air Force, 2018). The maximum duration of flight time is limited to 56 flight hours per seven consecutive days, 125 flight hours per 30 consecutive days, and 330 flight hours per 90 consecutive days. Distinctions are not made between manned and unmanned operations. Crew rest is compulsory for aircrew members prior to performing any duties involving aircraft operations and is a minimum of 12 non-duty hours before the flight duty period begins. Crew rest is free time for transportation, meals, and rest, and must provide an opportunity for at least eight hours of uninterrupted sleep. These requirements are the same for both manned and unmanned flight operations.

### *Army*

The U.S. Army is unique amongst the branches of the military because it does not provide a single, specific source of guidelines nor restrictions on flight duty time or rest requirements. Rather, guidelines for pilot duty and rest are provided across documents, including AR 95-1, AR 40-8, DA Pam 385–90, and in the Leaders Guide to Soldier Crew Endurance (Comperatore et al., 1997; U.S. Department of the Army, 2010, 2018, 2019). These resources are intended to provide guidance to commanders on developing programs tailored to the unit mission while also considering the importance of adequate rest and sleep. Commanders are also encouraged to consider the advice of the flight surgeon and aviation safety officer in designing their crew endurance and risk management programs.

### *Navy and Marine Corps*

The U.S. Navy (2016) outlines flight duty and rest requirements in the Naval Air Training and Operating Procedures Standardization (NATOPS) General Flight and Operating Instruments document. UAS flight crews are required to comply with all guidelines dictated in "Human Performance and Aeromedical Qualifications for Flight and Flight Support" (paragraph 8.3), which covers duty and rest requirements for manned flight operations. It is recommended that flight crews are not scheduled for continuous alert or flight duty in excess of 18 hours, which includes collateral duties, training, and off-duty activities. With the flight duty day, it is recommended that flight time not exceed three flights or 6.5 total hours for single-piloted aircraft and 12 hours for other aircraft. Additionally, a weekly maximum flight time limit is recommended at 30 hours for single-pilot operations and 50 hours for multi-pilot operations. Finally, when practical, flight personnel should not be scheduled for flight duties on more than six consecutive days.

Crew rest can be reduced to less than 12 hours in order to maintain a 24-hour work/rest schedule, but a shortened crew rest period (e.g., to maintain circadian rhythm) shall always include an opportunity for eight hours of uninterrupted sleep for every 24-hour period. If a flight duty day in excess of 18 hours is required, crews are to receive 15 hours of continuous off-duty time prior to scheduling any flight duty.

### *Coast Guard*

The U.S. Coast Guard (2018) Air Operations Manual provides guidance on aircrew flight duty and rest regulations. As with other military branches, aviation policies pertaining to manned aircraft also apply to unmanned aircraft, including flight scheduling standards and crew rest requirements. If a pilot conducts both manned and unmanned flight operations during the same 24-hour period, both operations are to count toward the total flight and crew mission hours. However, it is recommended that UAS crews are not scheduled for both types of operations in the same 24-hour period. The Coast Guard recommends that land-based UAS flight duty time not exceed 10 hours for single pilot operations and 14 hours for multiple pilot operations in a 24-hour period. Shipboard UAS aircrew should not exceed eight hours for single pilot operations and 12 hours for multiple pilot operations in a 24-hour period.

UAS crewmembers are to be given a minimum 30-minute rest break after no more than four consecutive flight hours, but it is highly recommended that crewmembers are relieved every two hours to minimize fatigue. Off-duty rest is dependent on the type of flight hours (single pilot versus multiple pilot), whether these hours were land-based or shipboard operations, and if the aircrew has flown on two or more consecutive days. The required off-duty hours ranged from 10 to 24 hours. UAS crewmembers deployed aboard ship may remain in duty status indefinitely, but may not exceed an average of eight flight hours per day for the previous seven days, and may not exceed individual flight hours per day as dictated by type of flight operation. If the average flight hours in a day exceeds eight hours (in the seven-day period), the crewmember is to receive 24 hours of rest. UAS crewmembers cannot fly more than 80 total hours in 14 consecutive days.

## Discussion

This report provides a review of research into UAS operator fatigue, and factors which may influence the operator's ability to safely operate a UAS or perform safety-related duties. Some factors identified include concerns that also pertain to manned operations, such as time of day, length of duty, shift work (i.e., rotating or changing schedules), fitness for duty, and acute and cumulative fatigue. Additional considerations may also include the amount of additional administrative duties assigned to the operator, unique HF considerations such as sensory isolation when operating a UAS or workload associated with operating multiple vehicles, and risks associated with accidents.

In general, there is a dearth of research into mitigating operator fatigue risks for civilian UAS operations. Research into military UAS operator well-being identified factors related to occupational stress that may contribute to safety and fatigue. Some of these additional factors include manning, tasking, scheduling, shift work, and additional administrative duties. The consequences of occupational burnout and occupational stress may impact the operator's ability to safely operate a UAS or perform safety-related duties due to increased workload and subsequent fatigue. As UAS endurance capabilities continue to increase with technological advancements, and as the civilian UAS industry expands, the concern with increased risk of operator fatigue and human error will continue to be a concern.

Based on military UAS operations research, some potential countermeasures to UAS operational stress – not specifically operator fatigue – include both policy and technological considerations. Scheduling should account for unique operating conditions, such as the number of UASs being flown or supervised by a single operator (e.g., dynamic staffing; see Hu et al, under review), potentially hazardous weather, and the difficulty of the task. Technology interventions may include the use of automation to potentially reduce fatigue by allowing multiple crews to operate one aircraft remotely. Although there are many contributing factors to UAS safety, the increasing complexity predicted for future civil UAS operations suggests that further research is needed to support the identification and mitigation of contributing factors to UAS operator fatigue.

## Future Directions

As current regulations stipulate, UAS operations over people and private properties are restricted and only authorized by an FAA exemption, and all operations are restricted to daytime only (unless exempted for nighttime operations). Although, the current project relates exclusively to considerations for UAS air carrier operations, the authors suspect that as the number of flight exemptions increase and are expanded to authorize UAS operations beyond just package delivery, so too, will the requirements for selection and training of UAS pilots/operators and perhaps even a requirement for medical certification.

Since this report concerns fatigue and its impact on UAS operations (and in particular the pilot or drone operator), an examination of fatigue factors has been reviewed and discussed in both Durham et al. (2021) and this report. It is anticipated that the results of a UAS survey, undertaken by Civil Aerospace Medical Institute (CAMI) personnel, will increase our understanding of the current state of UAS operations and help identify issues for future direction. Regardless of the survey outcomes, it has become clear that additional research is needed to improve our specific understanding of issues associated with scheduling, duty time, shift work (and rotations), workload, and other HF concerns to minimize risk, maximize safety, and improve operator performance during actual UAS operations.

As a first step, CAMI is currently conducting research into minimum UAS crew and staffing requirements and minimum UAS pilot KSA requirements (Hu et al., under review; Torrence et al., 2021), along with a market survey to assess current UAS industry operations and standards as it relates to UAS crew and staffing, UAS duty and rest requirements, and UAS pilot KSA and testing practices. Future research should continue to explore the relationship between the unique operational demands imposed on UAS operators, and concomitant stress and well-being experienced by the operators. Additionally, the interaction between HF concerns with workspace design and technology advancements should be taken into account. With the ever increasing interest and prevalence of UAS in air carrier and civil operations and with regard to this particular research effort, an examination of how HF and personal fitness for duty issues are managed, becomes highly significant.

We also anticipate that fatigue issues will be encountered in relation to Advanced Air Mobility (AAM). Certainly, there will be some degree of overlap and questions may arise as to how future directions align with the AAM research and development roadmaps and how autonomy plays a role in AAM concept of operations (CONOPS), and what does that mean for the future direction of UAS air carrier operations?

## Suggested Research Questions for Policy Development by Topic Area

Pertinent HF associated with UAS operator fatigue should consider further investigation of the research questions included under each topic area for policy development.

### Physiological Performance Metrics for Developing Requirements

Fatigue is often objectively defined by behavioral and physiological indicators. Much of the pilot and crew requirements for military are the same for both manned and unmanned operations. However, because of obvious differences in manned compared to unmanned environments, UAS may present additional challenges to FRMS. Understanding whether there are key differences in behavioral and physiological responses of operator fatigue in manned and unmanned operations is essential for developing UAS operator requirements. Several research questions could directly address these gaps:

- What physiological and objective performance metrics/indicators should be used to develop requirements related to pilot, crew rest, duty time, and shiftwork to manage operator fatigue in UAS operations?
- How do physiological indicators of fatigue/stress differ and affect performance in various UAS operations compared to manned operations?
- Are there different rates of fatigue accumulation in various UAS operational environments?
- Does UAS operator fatigue differ from manned operations?
- Does automation improve or worsen operator fatigue?
- What fatigue and performance tradeoffs come with different requirements?

**Operator KSAs and Training**

The information in which operators are trained on critically impacts the overall KSAs of UAS operators. Better understanding some of the basic research in UAS operations may support the development of training and testing requirements for UAS operations. It is likely that UAS operators should be cross-trained to fully understand the range of operations. Nonetheless, this document and others can support the development of accurate assessments that evaluate the performance of UAS operators and pilots in a standardized way. Examining each of these major components in an experimental way will provide guidance on training and testing requirements for UAS operators and pilots:

- What are the necessary knowledge, skills, and abilities that UAS pilots need in order to be adequately trained on how to properly manage their own occupational stress and fatigue?
- What KSAs protect UAS pilots from fatigue and are strongly related to performance?

**Systems Engineering of UAS Operations**

The manner in which a UAS operation is designed, integrated, and managed is critical to understanding what requirements are necessary for UAS operators to complete their duty assignments. Industry and regulatory agencies will have to commit to testing the capabilities and efficiency of various UAS air carrier operations compared to other UAS operations and manned operations. Research considering human factors, fatigue, system complexity, and the operational environment should directly support the design and restrictions of UAS certification. In addition, this should support the identification of the human factors issues related to operator fatigue in UAS and UAS air carrier operations. Several research questions should directly address these gaps:

- What are the operator fatigue-related HF issues that are present in the various types of UAS air carrier operations but not in the UAS operations described in the current research literature?
- Do UAS HF issues overlap/differ from those in manned operations?
- What are the fundamental tradeoffs in operator fatigue/occupational stress across UAS operations?
- How will this impact the structure of UASs, rest/crew/shift requirements and other operational risks to safety?
- What is an optimal crew size, how should they operate, and what are the necessary resources for effective crew resource management?
- What are appropriate risk assessment tools and risk-based decision making strategies for UAS operations?
- What UAS designs and user interfaces produce the best outcomes?

### Fatigue Risk Mitigations

When UAS operators experience fatigue, there needs to be appropriate safety controls in place to manage operational risks. There are likely to be risk mitigations used in manned operations that can be applied to unmanned operations, but it is likely that UAS-specific mitigations are necessary. Operational performance should be visualized in real-time to effectively mitigate operator fatigue and other safety risks. Industry and regulatory agencies should work together to develop the best fatigue risk mitigations. Several research questions related to this involve:

- What safety controls need to be in place to manage/prevent human error when/if an operator is fatigued?
- What fatigue/occupational stress factors should industry consider for pre-flight risk assessments?
- What modeling techniques and objective metrics can be used to assess and evaluate the level of risk for a given UAS operation and/or pilot?
- What fatigue risk mitigation strategies are most effective during operations?
- How should operator fatigue be managed by individuals and the organization to maintain as little risk as possible to people and property?

## Conclusions

The prevalence and use of UAS in civil and air carrier operations is bound to increase over time. However, there is limited research on operator fatigue in UAS operations. Industry subject matter experts and regulatory agencies should work together to help address the research gaps that will support policy development for UAS certification classes in air carrier operations. Advances in technology have increased the availability of UAS in civil operations, requiring the FAA to put forth a plan for safe and effective integration of UAS into the NAS (Huerta, 2018). The preliminary research outlined in this report is in accordance with the planned efforts of the UAS Roadmap. As safety is of the utmost concern, methodical steps must be taken to define safe duty and rest requirements for UAS pilots/operators based on empirical evaluation. A baseline can begin from regulation and lessons learned in manned aviation, shiftwork, and similar operations such as those outlined in this report and Durham et al. (2021). However, it will be likely that the final regulations for UAS operator requirements will differ from manned aviation operations as researchers uncover unique HF challenges associated with cognitive/perceptual loads, task saturation, and automation. For this reason, the suggested research questions provide a framework for understanding how operator fatigue in unmanned operations differ from manned operations, how to optimize/manage UAS operations, and how to apply lessons learned from fatigue research for rulemaking in UAS air carrier operations.

As UAS operations expand into civil aviation to perform such tasks as package/cargo delivery or air taxi services, certifications and regulations must be created for this new category of pilots. As identified in Durham et al., the development of duty and rest requirements for unmanned operations should be based on identified contributing factors to fatigue, such as shiftwork, task saturation, time of duty, etc. An aspect unique to unmanned operations compared to manned operations is the eventual ability to operate multiple UAVs during a single shift, which will have unique duty and rest regulations. As operations with multiple UAVs become commonplace, automation may play a larger role. Thus, duty and rest requirements will adapt as operators slowly step into the role of system monitoring rather than system operating, and future UAS regulations will have to consider this impact on pilot/operator fatigue.

## References


Alicia, T. (2015). *The bridging technique: Crossing over the modality shifting effect* [Unpublished doctoral dissertation]. The University of Central Florida, Orlando, Florida, USA.

Armour, C., & Ross, J. (2017). The health and well-being of military drone operators and intelligence analysts: A systematic review. *Military Psychology*, *29*(2), 83-98. https://doi.org/10.1037/mil0000149

Arrabito, G., Ho, G., Lambert, A., Rutley, M., Keillor, J., Chiu, A., Au, H., & Hou, M. (2010). *Uninhabited aerial vehicles: Preliminary findings in support of the Canadian Forces joint unmanned aerial vehicle surveillance target acquisition system project* (Report No. TR 2009-043). Defense Research and Development Canada.

Avers, K. B., King, S. J., Nesthus, T. E., Thomas, S., & Banks, J. (2009). *Flight attendant fatigue, part 1: National Duty, Rest, and Fatigue Survey* (Report No. DOT/FAA/AM-09/24). Federal Aviation Administration, Office of Aerospace Medicine. https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/2000s/media/200924.pdf

Avers, K. B., Nei, D., King, S. J., Thomas, S., Roberts, C., Banks, J. O., & Nesthus, T. E. (2011). *Flight attendant fatigue: A quantitative review of flight attendant comments* (Report No. DOT/FAA/AM-11/16). Federal Aviation Administration, Office of Aerospace Medicine. https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/2010s/media/201116.pdf

Brown, L., Schoutens, A. M. C., Whitehurst, G., Booker, T. J., Davis, T., Losinski, S., & Diehl, R. (2014). *The effect of blue light on pilot and flight attendant behavioural alertness*. Western Michigan University. http:/works.bepress.com/lori_brown/3

Bryant, M. R., Nesthus, T. E., & Rowley, C. (2016). *Evaluation of fatigue and responsibilities of cargo supervisors and flight mechanic cargo supervisors* (Report No. DOT/FAA/AM-16/6). Federal Aviation Administration, Office of Aerospace Medicine. https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/2010s/media/201606.pdf

Burmeister, H. C., Bruhn, W. C., Rodseth, O. J., & Porathe, T. (2014, April). Can unmanned ships improve navigational safety? In *Proceedings of the Transport Research Arena 2014* (pp. 1-10). Paris, France.

Caid, S., Hauret, D., Wolff, M., & Mollard, R. (2016). Fatigue study and discourse analysis of French Uninhabited Aerial Vehicle (UAV) operators to understand operational issues. In *Proceedings of the 15th Ergo'IA Conference.* New York, NY: ACM.

Caldwell, J. A. (2005). Fatigue in aviation. *Travel Medicine and Infectious Disease*, *3*(2), 85-96. https://doi.org/10.1016/j.tmaid.2004.07.008

Caldwell, J. A., Mallis, M. M., Caldwell, J. L., Paul, M. A., Miller, J. C., & Neri, D. F. (2009). Fatigue countermeasures in aviation. *Aviation, Space, and Environmental Medicine, 80*(1), 29-59. https://doi.org/10.3357/ASEM.2435.2009

Center for Robot-Assisted Search and Rescue. (2019). *Best practices to reduce fatigue in small unmanned aerial systems pilots.* http://crasar.org/just-in-time-guides-consultation/

Chappelle, W., Goodman, T., Reardon, L., & Thompson, W. (2014a). An analysis of post-traumatic stress symptoms in United States Air Force drone operators. *Journal of Anxiety Disorders, 28*(5), 480-487. https://doi.org/10.1016/j.janxdis.2014.05.003

Chappelle, W. L., McDonald, K. D., Prince, L., Goodman, T., Ray-Sannerud, B. N., & Thompson, W. (2014b). Symptoms of psychological distress and post-traumatic stress disorder in United States Air Force "drone" operators. *Military Medicine, 179*(8), 63-70. https://doi.org/10.7205/MILMED-D-13-00501

Chappelle, W. L., Salinas, A., & McDonald, K. (2011). *Psychological health screening of remotely piloted aircraft operators and supporting units* (Report No. RTO-MP-HFM-205). USAF School of Aerospace Medicine.

Clothier, R. A., Palmer, J. L., Walker, R. A., & Fulton, N. L. (2011). Definition of an airworthiness certification framework for civil unmanned aircraft systems. *Safety Science, 49*(6), 871-885. https://doi.org/10.1016/j.ssci.2011.02.004

Cook, S., Lacher, A., Maroney, D., & Zeitlin, A. (2012, January). UAS sense and avoid development-the challenges of technology, standards, and certification. In *50th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition* (pp. 1-10). Reston, VA: AIAA.

Comperatore C.A., Caldwell J.A., Caldwell J.L. (1997). *Leader's guide to crew endurance. Instructional brochure on crew work/ rest scheduling, circadian rhythms, fatigue, and fatigue countermeasures*. U.S. Army Aeromedical Research Laboratory and the U.S. Army Safety Center.

Coppin, G., Legras, F., & Saget, S. (2009, July). Supervision of autonomous vehicles: Mutual modeling and interaction management. In *International Conference on Engineering Psychology and Cognitive Ergonomics* (pp. 489-497). Springer. https://doi.org/10.1007/978-3-642-02728-4_52

Crandall, J. W., Cummings, M. L., & Nehme, C. E. (2008). *A predictive model for human-unmanned vehicle systems: Final report*. Massachusetts Institute of Technology, Department of Aeronautics and Astronautics.

Cruz, C., Detwiler, C., Nesthus, T., & Boquet, A. (2002). *A laboratory comparison of clockwise and counter-clockwise rapidly rotating shift schedules, Part I: Sleep* (Report No. DOT/FAA/AM-02/8). Federal Aviation Administration, Office of Aerospace Medicine. https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/2000s/media/0208.pdf

Dalamagkidis, K., Valavanis, K. P., & Piegl, L. A. (2008, June). A survey of unmanned aircraft systems regulation: Status and future perspectives. In *2008 16th Mediterranean Conference on Control and Automation* (pp. 717-723). Ajaccio, France: IEEE. https://doi.org/10.1109/MED.2008.4602250

De La Torre, G. G., Ramallo, M. A., & Cervantes, E. (2016). Workload perception in drone flight training simulators. *Computers in Human Behavior*, *64*, 449-454. https://doi.org/10.1016/j.chb.2016.07.040

Della Rocco, P. S. (1999). *The role of shift work and fatigue in air traffic control operational errors and incidents* (Report No. DOT/FAA/AM-99/2). Federal Aviation Administration, Office of Aerospace Medicine.

https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/1990s/media/AM99-02.pdf

Della Rocco, P. S., & Nesthus, T. E. (2005). Shiftwork and air traffic control: Transitioning research results to the workforce. In B. Kirwan, M. Rodgers, & D. Schafer (Eds.), *Human factors impacts in air traffic management*. Ashgate Publishing.

Durham, J. D., Mofle, T. C., Nesmith, B. L., Hu, P., Fercho, K. A., & Nesthus, T. E. (2021). *Literature Review and Annotated Bibliography (1990 – 2019): Duty Time, Shift Work, and Operator Fatigue for Consideration of Unmanned Aircraft Systems in Air Carrier Operations*. Federal Aviation Administration, Office of Aerospace Medicine.

European Commission. (2019, June). Commission implementing regulation (EU) 2019/947 of 24 May 2019 on the rules and procedures for the operation of unmanned aircraft. *Official Journal of the European Union, 62*(L152).

European Union Aviation Safety Agency. (2019). *Effectiveness of flight time limitation (FTL).* EASA.

Federal Aviation Administration. (2013a). *Fatigue risk management for aviation safety* (Advisory Circular No. 120-103A). U.S. Department of Transportation, Federal Aviation Administration. https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentid/1021088

Federal Aviation Administration. (2013b). Chapter 58 management of aviation fatigue: Section 1 review and acceptance of fatigue risk management plans (FRMP). In *Flight standards information management system (Vol. 3)*. U.S. Department of Transportation, Federal Aviation Administration. https://fsims.faa.gov/wdocs/8900.1/change%20history/summary%20of%20changes/00_01_summary%20of%20chg301.htm

Federal Aviation Administration. (2019). *Part 135 pilot rest and duty rules ARC charter*. U.S. Department of Transportation, Federal Aviation Administration.

Freund, D. M., Knipling, R. R., Landsburg, A. C., Simmons, R. R., & Thomas, G. R. (1995). *A holistic approach to operator alertness research* (Report No. 950636). U.S. Department of Transportation.

Gawron, V. J. (2016). Summary of fatigue research for civilian and military pilots. *IIE Transactions on Occupational Ergonomics and Human Factors, 4*(1), 1-18. https://doi.org/10.1080/21577323.2015.1046093

Gawron, V. J., Kaminski, M. A., Serber, M. L., Payton, G. M., Hadjimichael, M., Jarrott, W. M., Estes, S. L., & Neal II, T. A. (2011). *Human performance and fatigue research for controllers—Revised* (Report No. MTR100316). The MITRE Corporation.

Goode, J. H. (2003). Are pilots at risk of accidents due to fatigue? *Journal of Safety Research, 34*(3), 309-313. https://doi.org/10.1016/S0022-4375(03)00033-1

Gregory, K. B., Winn, W., Johnson, K., & Rosekind, M. R. (2010). Pilot fatigue survey: Exploring fatigue factors in air medical operations. *Air Medical Journal, 29*(6), 309-319. https://doi.org/10.1016/j.amj.2010.07.002

Gupta, S. G., Ghonge, M. M., & Jawandhiya, P. M. (2013). Review of Unmanned Aircraft System (UAS). *International Journal of Advanced Research in Computer Engineering & Technology (IJARCET), 2(4)*, 1646-1658. https://dx.doi.org/10.2139/ssrn.3451039

Hardison, C. M. (2018). *Stress and dissatisfaction in the Air Force's remotely piloted aircraft community: Focus group findings* (Report No. RR-1756-AF). Rand Corporation.

Hayhurst, K. J., Maddalon, J. M., Miner, P. S., DeWalt, M. P., & McCormick, G. F. (2006, October). Unmanned aircraft hazards and their implications for regulation. In *2006 IEEE/AIAA 25TH Digital Avionics Systems Conference* (pp. 1-12). Piscataway, NJ: IEEE. https://doi.org/10.1109/DASC.2006.313735

Hobbs, A., Avers, K. B., & Hiles, J. J. (2011). *Fatigue risk management in aviation maintenance: Current best practices and potential future countermeasures* (Report No. DOT/FAA/AM-11/10). Federal Aviation Administration, Office of Aerospace Medicine. https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/2010s/media/201110.pdf

Hobbs, A., & Lyall, B. (2016). Human factors guidelines for unmanned aircraft systems. *Ergonomics in Design*, *24*(3), 23-28. https://doi.org/10.1177%2F1064804616640632

Hoepf, M., Middendorf, M., Epling, S., & Galster, S. (2015). *Physiological indicators of workload in a remotely piloted aircraft simulation* (Report No. AFRL-RH-WP-TR-2015-0092). Air Force Research Lab.

Hopcroft, R., Burchat, E., & Vince, J. (2006). *Unmanned aerial vehicles for maritime patrol: Human factors issues* (Report No. DSTO-GD-0463). Australian Government Department of Defence, Defence Science and Technology Organisation.

Howse, W. R. (2011). *Knowledge, skills, abilities, and other characteristics for remotely piloted aircraft pilots and operators* (Report No. AFCAPS-FR-2011-0006). Air Force Personnel Center.

Hu, P. T., Nelson, B., Nesmith, B, L., Thomas, G. F., & Williams, K. W. (under review). *Annotated bibliography (1997 – 2019): Crew and staffing requirements of unmanned aircraft systems in air carrier operations.* Federal Aviation Administration, Office of Aerospace Medicine.

Huerta, M. (2018). *Integration of civil unmanned aircraft systems (UAS) in the national airspace system (NAS) roadmap* (2nd Ed.). Federal Aviation Administration.

International Civil Aviation Organization. (2015). *Fatigue management guide for airline operators* (2nd ed.). ICAO.

International Civil Aviation Organization. (2016a). *Fatigue management guide for general aviation operators of large and turbojet aeroplanes* (1st ed.). ICAO.

International Civil Aviation Organization. (2016b). *Fatigue management guide for air traffic service providers* (1st ed.). ICAO.

International Civil Aviation Organization. (2016c). *Manual for the oversight of fatigue management approaches* (Doc Series No. 9966) (2nd ed.). ICAO.

International Civil Aviation Organization. (2019). *Unmanned aircraft system traffic management (UTM) request for information*. ICAO.

Jay, S. M., Aisbett, B., Sprajcer, M., & Ferguson, S. A. (2015). Sleeping at work: Not all about location, location, location. *Sleep Medicine Reviews*, *19*, 59-66. https://doi.org/10.1016/j.smrv.2014.04.003

Krishnan, V. K., Dasari, D., & Ding, L. (2014). *EEG correlates of fluctuation in cognitive performance in an air traffic control task* (Report No. DOT/FAA/AM-14/12). Federal Aviation Administration, Office of Aerospace Medicine. https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/2010s/media/201412.pdf

Maddalon, J. M., Hayhurst, K. J., Morris, A., & Verstynen, H. (2013, August). Considerations of unmanned aircraft classification for civil airworthiness standards. In *Guidance, Navigation, and Control and Co-located Conferences*, Boston, MA: AIAA.

Man, Y., Lundh, M., Porathe, T., & MacKinnon, S. (2015). From desk to field-Human factor issues in remote monitoring and controlling of autonomous unmanned vessels. *Procedia Manufacturing, 3*, 2674-2681. https://doi.org/10.1016/j.promfg.2015.07.635

Manning, S. D., Rash, C. E., Leduc, P. A., Noback, R. K., & McKeon, J. (2004). *The role of human causal factors in US Army unmanned aerial vehicle accidents* (Report No. USAARL-2004-11). Army Aeromedical Research Lab.

McCauley, D., & Nesthus, T. (2017). Status of FAA air traffic control fatigue interventions 2013-2016. In *19th International Symposium on Aviation Psychology* (pp. 160-166). Dayton, OH: Wright State University. https://corescholar.libraries.wright.edu/isap_2017/39

Narayan, P. P., Wu, P. P., Campbell, D. A., & Walker, R. A. (2007). An intelligent control architecture for unmanned aerial systems (UAS) in the national airspace system (NAS). In *2nd International Unmanned Air Vehicle Systems Conference.* Melbourne, Australia.

Nealley, M. A., & Gawron, V. J. (2015). Effects of fatigue on air traffic controllers. *The International Journal of Aviation Psychology, 25*(1), 14-47. https://doi.org/10.1080/10508414.2015.981488

Nix, S., Gossett, K., & Shepherd, A. D. (2013). An investigation of pilot fatigue in helicopter emergency medical services. *Air Medical Journal, 32*(5), 275-279. https://doi.org/10.1016/j.amj.2013.04.001

Norton, T. (2016). *Staffing for unmanned aircraft systems (UAS) operations* (Report No. P-5253). Institute for Defense Analyses.

Oncu, M., & Yildiz, S. (2014). *An analysis of human causal factors in unmanned aerial vehicle (UAV) accidents* (Master's thesis). Monterey, CA: Naval Postgraduate School. Retrieved from: http://hdl.handle.net/10945/44637

Ouma, J. A., Chappelle, W. L., & Salinas, A. (2011). *Facets of occupational burnout among US Air Force active duty and National Guard/reserve MQ-1 predator and MQ-9 reaper operators* (No. AFRL-SA-WP-TR-2011-0003). Air Force Research Lab.

Paullin, C., Ingerick, M., Trippe, D. M., & Wasko, L. (2011). *Identifying best bet entry-level selection measures for US Air Force remotely piloted aircraft (RPA) pilot and sensor operator (SO) occupations* (Report No. HRRO-FR-11-64). Human Resources Research Organization.

Pavlas, D., Burke, C. S., Fiore, S. M., Salas, E., Jensen, R., & Fu, D. (2009). Enhancing unmanned aerial system training: A taxonomy of knowledge, skills, attitudes, and methods. *Proceedings of the*

*Human Factors and Ergonomics Society Annual Meeting, 53*(26), 1903-1907. https://doi.org/10.1177%2F154193120905302604

Phillips, A., Sherwood, D., Greenberg, N., & Jones, N. (2019). Occupational stress in remotely piloted aircraft system operators. *Occupational Medicine*, *69*(4), 244-250. https://doi.org/10.1093/occmed/kqz054

Porathe, T., Prison, J., & Man, Y. (2014, February). Situation awareness in remote control centres for unmanned ships. *Proceedings of Human Factors in Ship Design & Operation*. London, UK: The Royal Institution of Naval Architects.

Roma, P. G., Mallis, M. M., Hursh, S. R., Mead, A. M., & Nesthus, T. E. (2010). *Flight attendant fatigue recommendation II: Flight attendant work/rest patterns, alertness, and performance assessment* (Report No. DOT/FAA/AM-10/22). Federal Aviation Administration, Office of Aerospace Medicine. https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/2010s/media/201022.pdf

Rudin-Brown, C. M., Harris, S., & Rosberg, A. (2018). How shift scheduling practices contribute to fatigue amongst freight rail operating employees: Findings from Canadian accident investigations. *Accident Analysis & Prevention, 126*, 64-69. https://doi.org/10.1016/j.aap.2018.01.027

Samel, A., Wegmann, H-M., & Vejvoda, M. (1997). Aircrew fatigue in long-haul operations. *Accident Analysis and Prevention, 29*(4), 439-452. https://doi.org/10.1016/S0001-4575(97)00023-7

Scheiman, T., Chappelle, W., & Sanford, E. (2018). *U. S. Air Force special operations command remotely piloted aircraft operator fatigue levels and compensatory strategies* (Report No. AFRL-SA-WP-TR-2018-0013). Air Force Research Lab.

Schroeder, D. J., Rosa, R. R., Witt, L. A., & Banks, B. (1995). *Some effects of 8-vs 10-hour work schedules on the test performance/alertness of air traffic control specialists* (Report No. DOT/FAA/AM-95/32). Federal Aviation Administration, Office of Aviation Medicine. https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/1990s/media/AM95-32.pdf

Schroeder, D. J., Touchstone, R. M., Stern, J. A., Stoliarov, N., & Thackray, R. I. (1994). *Maintaining vigilance on a simulated ATC monitoring task across repeated sessions* (Report No. DOT/FAA/AM-94/6). Federal Aviation Administration, Office of Aviation Medicine. https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/1990s/media/AM94-06.pdf

Singh, G., Roy, R. N., & Chanel, C. P. C. (2019, February). Towards multi-UAV and human interaction driving system exploiting human mental state estimation. In *10th International Conference on Bioinformatics Models, Methods and Algorithms (BIOINFORMATICS 2019)*. Prague, Czech Republic. https://hal.archives-ouvertes.fr/hal-02042960

Smithsonian Magazine (2013). Unmanned Aerial Vehicles. https://www.smithsonianmag.com/arts-culture/unmanned-drones-have-been-around-since-world-war-i-16055939/

Sprengart, S. M., Neis, S. M., & Schiefele, J. (2018). Role of the human operator in future commercial Reduced Crew Operations. In *2018 IEEE/AIAA 37th Digital Avionics Systems Conference*. New York City, NY: IEEE. https://doi.org/10.1109/DASC.2018.8569803

Stern, J. A., Boyer, D., & Schroeder, D. J. (1994). *Blink rate as a measure of fatigue: A review* (Report No. DOT/FAA/AM-94/17). Federal Aviation Administration, Office of Aviation Medicine. https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/1990s/media/AM94-17.pdf

Strauss, S. (2006). *Pilot fatigue*. Houston, TX: Johnson Space Center. http://aeromedical.org/Articles/Pilot_Fatigue.html

Szabolcsi, R. (2016). UAV operator training – Beyond minimum standards. *Scientific Research and Education in the Air Force – AFASES, 1*, 193-198.

Thompson, W. T., Lopez, N., Hickey, P., DaLuz, C., Caldwell, J. L., & Tvaryanas, A. P. (2006). *Effects of shift work and sustained operations: Operator performance in remotely piloted aircraft (OP-REPAIR)* (Report No. HSW-PE-BR-TR-2006-0001). Air Force Research Laboratory.

Torrence, B., Nelson, B., Thomas, G. F., Nesmith, B. L., & Williams, K. W. (2021). *Annotated bibliography (1990 – 2019): Knowledge, skills, and tests for unmanned aircraft systems (UAS) air carrier operations*. Federal Aviation Administration, Office of Aerospace Medicine.

Tvaryanas, A. P. (2006). Human systems integration in remotely piloted aircraft operations. *Aviation, Space, and Environmental Medicine, 77*(12), 1278-1282.

Tvaryanas, A. P., & MacPherson, G. D. (2009). Fatigue in pilots of remotely piloted aircraft before and after shift work adjustment. *Aviation, Space, and Environmental Medicine, 80*(5), 454-461. https://doi.org/10.3357/ASEM.2455.2009

Tvaryanas, A. P., Platte, W., Swigart, C., Colebank, J., & Miller, N. L. (2008). *A resurvey of shift work-related fatigue in MQ-1 Predator unmanned aircraft system crewmembers* (Report No. NPS-OR-08-001). Naval Postgraduate School. http://hdl.handle.net/10945/759

U.S. Coast Guard. (2018, October 26). *Air Operations Manual*: *COMDTINST M3710.1H*. U.S. Department of Homeland Security. https://media.defense.gov/2018/Nov/01/2002058346/-1/-1/0/CIM_3710_1H.PDF

U.S. Department of the Air Force. (2018). *Air Force Guidance Memorandum to AFI 11-202V3, General Flight Rules* (Report No. AFI 11-202V3_AFGM2018-01). U.S. Department of Defense.

U.S. Department of the Army. (2010, February 24). *Army aviation accident prevention program: Pamphlet 385-90*. https://armypubs.army.mil/epubs/DR_pubs/DR_a/pdf/web/p385_90.pdf

U.S. Department of the Army. (2018, March 22). *Aviation flight regulations: Army regulation 95-1*. https://armypubs.army.mil/epubs/DR_pubs/DR_a/pdf/web/ARN5966_AR_95-1_WEB_FINAL.pdf

U.S. Department of the Army. (2019, March 22). *Temporary flying restriction due to exogenous factors affecting aircrew efficiency: Army regulation 40-8*. https://armypubs.army.mil/epubs/DR_pubs/DR_a/pdf/web/ARN7194_AR40-8_FINAL.pdf

U.S. Department of the Navy. (2016, May 5). *NATOPS general flight and operating instructions manual: CNAF M-3710.7*. https://www.public.navy.mil/airfor/vaw120/Documents/CNAF%20M-3710.7_WEB.PDF

Van Camp, R. O. (2009). Zolpidem in fatigue management for surge operations of remotely piloted aircraft. *Aviation, Space, and Environmental Medicine*, *80*(6), 553-555. https://doi.org/10.3357/ASEM.2460.2009

Wahlström, M., Hakulinen, J., Karvonen, H., & Lindborg, I. (2015). Human factors challenges in unmanned ship operations – Insights from other domains. *Procedia Manufacturing*, *3*, 1038-1045. https://doi.org/10.1016/j.promfg.2015.07.167

Waraich, Q. R., Mazzuchi, T. A., Sarkani, S., & Rico, D. F. (2013). Minimizing human factors mishaps in unmanned aircraft systems. *Ergonomics in Design*, *21*(1), 25-32. https://doi.org/10.1177%2F1064804612463215

Washington, A., Clothier, R. A., & Silva, J. (2017). A review of unmanned aircraft system ground risk models. *Progress in Aerospace Sciences*, *95*, 24-44. https://doi.org/10.1016/j.paerosci.2017.10.001

Wilson, N. D., Tavakolian, K., & Fazel-Rezai, R. (2016). Systems and methods to provide feedback to pilot/operator by utilizing integration of navigation and physiological monitoring. U.S. Patent Application No. 15/153,198.

Wohleber, R. W., Matthews, G., Lin, J., Szalma, J. L., Calhoun, G. L., Funke, G. J., Chiu, C.-Y. P., & Ruff, H. A. (2019). Vigilance and automation dependence in operation of multiple unmanned aerial systems (UAS): A simulation study. *Human Factors*, *61*(3), 488-505. https://doi.org/10.1177%2F0018720818799468

Wolf, H. G. (2013, March). Unmanned aircraft systems integration into the national airspace. In *IEEE Aerospace Conference* (pp. 1-16). New York City, NY: IEEE. https://doi.org/10.1109/AERO.2013.6496918