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Research Plan to Investigate Highly Automated Vehicle (HAV) Human Factors Implications

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Executive Summary

The Federal Aviation Administration (FAA) NextGen Human Factors Division developed this Research Plan to investigate the air traffic control human factors considerations of integrating Highly Automated Vehicles (HAVs) into the National Airspace System (NAS). HAVs have been touted as solving significant safety problems and reducing human factors issues as 80-90% of aviation accidents are due to human error. The introduction of HAVs into the NAS raises complicated questions concerning safe and reliable operations, roles and responsibilities of humans and automation, and Air Traffic Control (ATC) and Air Traffic Management (ATM) interactions. Urban Air Mobility[1] (UAM) is expected to introduce HAVs into the NAS to enable high frequency, low altitude, short duration operations in and around major metropolitan areas. UAM operations make a good case study to assess and analyze air traffic control human factors implications for integrating HAVs into the NAS in the near future.

UAM enables highly automated, cooperative, passenger or cargo-carrying air transportation services in and around urban areas. The UAM concept projects operational and economic feasibility resulting from technological advancements (e.g., on-board Detect and Avoid (DAA) systems, trajectory deconfliction advancements) and decreasing costs associated with ride-share models. UAM operations are expected to occur within the proposed UAM environment, termed "UAM Corridors". The envisioned future state of UAM operations includes increasing levels of vehicle automation and operational tempo across a range of environments including major metropolitan areas and the surrounding suburbs.

As with HAVs in general, early UAM operations are expected to evolve in a "crawl-walk-run" fashion. Early UAM operations will likely develop additional assistive automation beyond current ATM aircraft (e.g., DAA) and have a low operational tempo with a pilot onboard. Human factors research will be foundational to inform UAM concepts and assumptions regarding ATC and ATM operational impacts and ensure readiness for increased operational tempos and automation support. As UAM operations drive towards a mature state, human factors research must support continued optimization of system efficiency, enhanced safety, and minimized impacts to ATC and ATM operations.

This research plan provides an overview of air traffic control human factors research areas and questions that warrant further investigation and analysis as HAV concepts are developed. This document focuses on ATC operational considerations and interactions with HAVs. This document does not prescribe specific research designs. This research plan provides an overview of critical areas for air traffic control human factors investigation to safely implement HAVs into the current NAS infrastructure. Human Factors research must be included from the early design phase and throughout maturing levels to ensure humans within the system behave as expected and the system is performing optimally.

[1] FAA UAM ConOps v1.0, June 2020

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Version History

Date	Revision	Version
1/19/2021	Initial Working Draft	0.1
3/2/2021	Final	1.0
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1 Introduction

1.1 Overview

Highly Automated Vehicles (HAVs) possess advanced automation that will eventually place the operator over the control loop of one or more aircraft flying autonomously. The shift from aircraft with a pilot onboard directly controlling the flight path to aircraft flying autonomously with a ground-based operator monitoring the flight and interacting with air traffic control and management facilities will require significant changes to how traffic in the National Airspace System (NAS) is controlled. The influx of these new operations in addition to other emerging operations and technologies (e.g., Unmanned Aircraft Systems (UAS)) present unique questions about their impact on Air Traffic Control (ATC) and Air Traffic Management (ATM) in several human factors areas including workload, situational awareness, performance, trust and reliance on automation, human-system interaction, decision making, and communication/coordination.

In the future, HAVs are expected to conduct many operations currently performed by piloted aircraft. Operations could range from high-altitude long-duration missions flown by lighter-than-air aircraft to autonomous cargo flights in what is now Class A airspace to short-duration low-altitude flights carrying packages and passengers from point to point. The many differing HAV operations under consideration are at varying levels of maturity, from initial hypothetical applications to rapidly maturing Concept of Operations (ConOps).

In order to best approach developing a research plan, it was decided to use the Urban Air Mobility (UAM) concept as a guide due to its relative maturity and likelihood of being the first to begin operation. UAM is a focus area for the Federal Aviation Administration (FAA), National Aeronautics and Space Administration (NASA), and Industry and represents a nearer-term challenge for incorporating HAVs into the NAS. UAM enables highly automated, cooperative, passenger or cargo-carrying air transportation services in and around urban areas. As with HAVs in general, the envisioned future state for UAM operations includes increasing levels of autonomy and operational tempo across a range of environments including major metropolitan areas and the surrounding suburbs.

The UAM ConOps Version 1.0, released by the FAA on June 26, 2020, provides an initial, foundational perspective supporting the introduction and incorporation of UAM operations into the NAS. In the near-term, UAM operations will be low-density, have a pilot onboard with assistive automation, and be constrained to a small set of fixed routes (termed UAM Corridors) similar to today's helicopter routes in and around major metropolitan areas.

In the mature state, technology and vehicle designs will evolve and proliferate, and UAM vehicles will involve higher levels of automation ultimately including operations conducted as HAVs. This evolution of vehicle capability, operational types, and technologies presents a model operation that can be used to identify where the need for continued air traffic control human factors evaluations and assessments is greatest as the traditional role of the pilot shifts to one more supervisory in nature. Specifically, the anticipated increased degree of automation presents unique barriers regarding human-system interactions and the roles, demands, and expectations of human agents within the system.

1.2 Document Purpose and Scope

The goal of this document is to analyze and assess the human factors implications for air traffic controllers from integrating HAVs into the NAS in the near-, mid-, and far-terms. UAM is likely to be the earliest HAV operation having significant impacts to ATM/ATC operations, making UAM a focused case study for HAV integration. This document provides an overview of air traffic control human factors research areas and questions that warrant further investigation and analysis to minimize NAS safety and efficiency risks. Specific research design is a focus for the next phase of research and therefore not included in this document.

The scope of this research plan focuses on ATC operational considerations with HAVs. There are many more complex Human Factors (HF)-related issues that are not covered in this document such as technologies, vehicle operations, public acceptance and trust, impact on other NAS users, and varying levels of each with regard to increasing automation. This report is not intended to minimize or omit these other issues as less than foundational considerations to overall operational feasibility; these items are just beyond the scope of this document. This research plan will provide a prioritized list of areas that need investigation and recommendations for how to best approach the research.

1.3 Document Organization

This document is organized as follows:

Section 1: Introduction – provides background and objective of the human factors research plan

Section 2: Integrating Highly Automated Vehicles into the NAS – a discussion related to the integration of current and evolving HAV operations

Section 3: Air Traffic Control Human Factors Research Considerations in an Evolving HAV Operational Environment – a high-level discussion centered around areas of research necessary to ensure safe and scalable UAM operations

Section 4: Notional Timeline and Sequencing of Events

Section 5: Conclusion

Appendix A – References

Appendix B – Acronyms

Appendix C – Glossary

Appendix D – Recommendations for Specific Air Traffic Control Human Factors Research Questions

2 Integrating Highly Automated Vehicles into the NAS

The NAS continues to evolve and accommodate changing aircraft types and technologies that are growing in operational demand. Highly Automated Vehicles (HAVs) (e.g., UAS, UAM) have significant areas of growth creating a variety of issues and novel challenges as their operations across both controlled and uncontrolled airspace are expected to exponentially increase.

Integrating HAV operations into the NAS will be an evolutionary process. Several types of HAV operations are moving forward (e.g., UAS operations above FL600, operations in urban areas, small UAS operations below 400 ft). UAM operations are gaining momentum in the near-term as a focus area for the FAA, NASA, and Industry. UAM operations are envisioned to occur at lower altitudes (below 5,000 feet Above Ground Level (AGL)) with scaling constraints as those seen with UAS operations. Current ATM and ATC infrastructure is not expected to support routine UAM operations. Instead, a unique ecosystem is being planned to establish and incorporate UAM operations into the NAS while minimizing impacts to traditional ATC services and ATM. Even so, there will be effects on controllers from incorporating HAV operations in the NAS, such as changes to airspace, off-nominal events that have the potential to result in conflicts between HAVs and ATM aircraft, or adding new communications channels with new actors.

As a more near-term case study of how HAVs will be integrated into the NAS, UAM provides a clear example of how the introduction of HAVs will occur and the air traffic control human factors issues that should be addressed. It is assumed that concepts described in ConOps v1.0 will be generalizable from the UAM domain to the wider HAV ecosystem. This section describes the evolution of UAM operations, UAM Corridors, and UAM operational assumptions, as described in ConOps v1.0, and their applicability to more general HAV operations.

2.1 UAM/HAV Evolution

Fully integrating HAVs into the NAS will occur gradually. In the same way, as depicted in Figure 1[2], UAM operations will evolve with operations moving progressively towards a mature state where operations occur at a high tempo and additional structure, regulatory changes, and advanced technology will likely be needed.

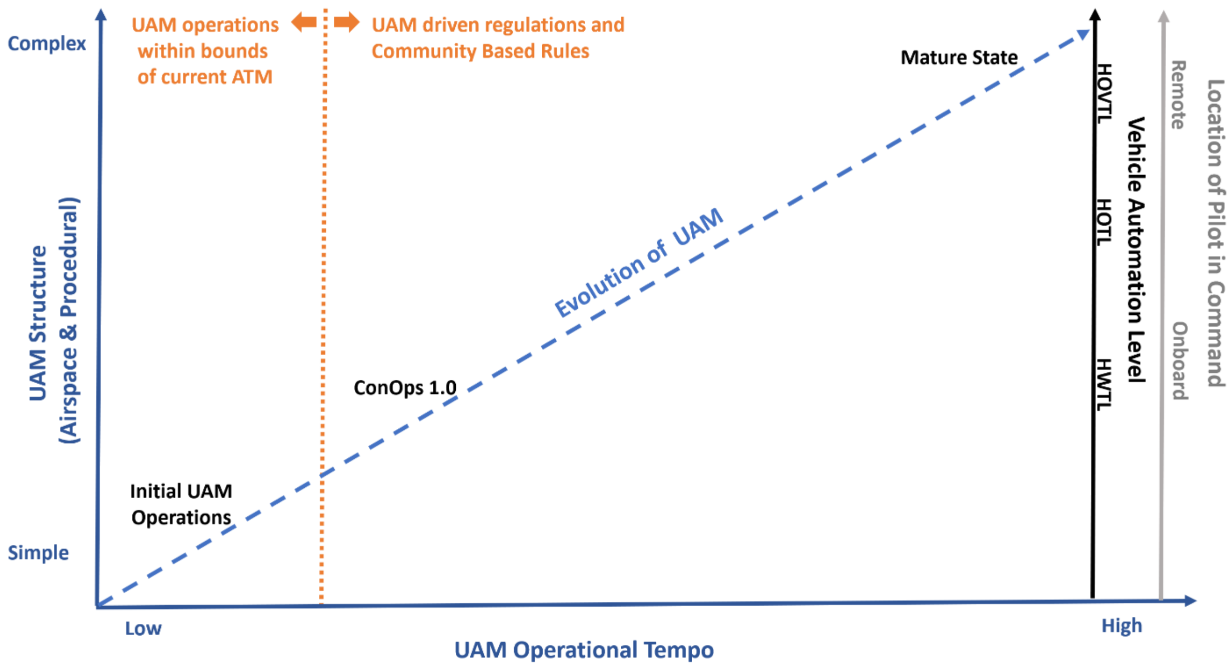

Figure 1: Evolution of the UAM Operating Environment

The industry vision involves incorporating new aircraft designs and systems technologies which may include electric vertical takeoff and landing (eVTOL) capabilities that allow for operations between various locations (e.g., metropolitan commutes). These new technologies will potentially allow for these operations to be utilized more frequently and in more locations than are currently performed by conventional aircraft. Such highly automated systems will enable the pilot, either onboard or remote, to transition from the role of the hands-on operator to that of a system monitor/supervisor in a Human-Over-The-Loop (HOVTL) system.

Similarly, other HAV operational concepts can be expected to follow a similar path as that shown in figure 1. As tempo increases, ecosystem complexity and vehicle autonomy will also increase. Thus, human factors effects that appear through the evolution of the UAM operating environment will likely be seen in other HAV operations.

2.2 Operational Corridors

UAM Corridors are introduced to enable high operational volumes of HAVs operating in the NAS and can be used to derive a set of air traffic control human factors considerations that will be in play when integrating HAVs into the NAS as a whole. These UAM Corridors enable reaching the mature state of safe and efficient UAM operations, without the need for tactical ATC separation

[2] FAA UAM ConOps v1.0, June 2020

services. UAM Corridors are the primary mechanism of separation between UAM operations and ATM operations that do not meet UAM performance and participation requirements. As proposed, UAM Corridors will not be separate classes of airspace. Therefore, the introduction of UAM Corridors will create a unique paradigm shift for ATC in controlled airspace (e.g., Class B) where these operations are occurring without requiring traditional ATC services for the airspace of operation. Any operator that meets the UAM Corridor performance and participation requirements may operate in, or cross, the UAM Corridor.

ATC will be aware of UAM Corridors as part of general awareness of the airspace for which ATC is responsible. Other NAS Users will be aware of UAM Corridors through airspace familiarization associated with flight planning or ATC flight plan approval or advisories. Initially, UAM Corridors will support point-to-point operations between two vertiports. However, as UAM operations evolve, UAM Corridors may form a network of available routing between vertiports.

UAM operations occurring within a UAM Corridor apply the following assumptions:

- UAM aircraft identification and location information are available to the UAM operator and to the Provider of Services for UAM (PSU) Network but not via Automatic Dependent Surveillance - Broadcast (ADS-B) Out or transponders. As a result, ATC systems such as STARS or ERAM will not depict UAMs operating within corridors. Should the vehicle desire to operate outside the UAM Corridor (especially in Class B airspace) they will be required to carry all onboard equipment other non-UAM vehicles require (e.g., ADS-B out).

- Two-way voice communication with ATC will not be conducted inside UAM Corridors during nominal operations.

- The UAM operator will not receive ATC clearances nor ATC authorizations for operations occurring within UAM Corridors.

- Operational ATC involvement is limited to setting UAM Corridor availability based on the ATC operational design, receiving UAM Corridor status for awareness of which UAM Corridors have active operations, and responding to UAM off-nominal events as needed.

Similar assumptions can be made about how other HAVs could be expected to be handled as well. While these assumptions are aimed at reducing ATC workload, further investigation is warranted to assess all human factors implications to ATC.

3 Air Traffic Control Human Factors Considerations in an Evolving HAV Operational Environment

3.1 Research Area Approach and Impact Analysis

As the definition of the operational environment concept for UAM operations has been developed, human factors and ATC Subject Matter Experts (SMEs) have assessed and identified areas needing further research and analysis for air traffic control human factors implications that are generalizable to the wider range of HAV operations. As UAM operational concepts have been reviewed and developed, broad research areas and questions were formed and analyzed to identify the following areas of potential human factors impacts on ATC applicable to HAVs:

- Workload
- Stress
- Situational awareness
- Communication
- Automation
- Performance
- Training Cognition
- Teamwork

Within the research areas, research questions were methodically developed and refined to include measurable outcomes, testing variables, research methodologies, and inter-dependencies.

3.2 Human Factors Methodologies

This section discusses common human factors research methodologies at a high level to accomplish the proposed research questions detailed in Table D1, which may be further refined or modified depending upon the specific research design. The research methodologies described should be incorporated based on a sliding scale, where research should be progressive and begin with tabletop exercises (e.g., Task Analysis), where possible, before advancing to more complex and expensive methodologies (e.g., Human-In-The-Loop (HITL) simulation).

3.2.1 Task Analysis

A Task Analysis is a method used by Human Factors practitioners to develop a systematic understanding of a concept/system by decomposing goals and tasks into smaller subtasks and examining the relationships between these subtasks. A Task Analysis allows for systematic comparisons between the capabilities and demands of a concept, the steps users take to achieve the goals, the contextual and situational elements of the work, identification of potential break points within a system, and gaining insight into where the design of a new concept can improve task performance.

The primary steps involved in conducting a Task Analysis are:

1. Identifying the high-level goal that the user is trying to achieve

2. Identifying the tasks necessary to accomplish the goal

3. Decomposing the identified tasks into the smaller subtasks required to achieve the larger task. This step is iterative and repeated until the desired level of granularity is achieved.

4. Analyzing subtasks and their relationships to identify mismatches, break points, and potential areas for error. Additionally, this analysis can be used to generate design solutions that minimize the risk of error and increase the likelihood of achieving desired goals.

There are several forms of Task Analyses available to concept developers. Common forms used include:

- Decision and Action Flow Diagrams
- Hierarchical Task Analysis (HTA)
- Cognitive Task Analysis (CTA)
- Goals, Operators, Methods, and Selection Rules (GOMS) Modeling

3.2.1.1 Decision and Action Flow Diagrams

Decision and Action Flow Diagrams are flow charts based on binary choice decisions and intervening operations that show the actions, steps, and questions in decision-making tasks. Decision and Action charts can be easily trained, and workers usually find them useful in formulating their mental plans involving decision-making, time-sharing, and other complex conditions and contingencies. A major shortfall associated with these tools is that they involve only a single level of task description. When the task being analyzed is overly complex (e.g., managing multiple flows of traffic in a constrained environment), Decision and Action Flow Diagrams can rapidly become overly cumbersome and difficult to follow.

3.2.1.2 Hierarchical Task Analysis

A Hierarchical Task Analysis (HTA) is a systematic method of describing how work is organized to meet the overall objective of the job. HTAs involve identifying the overall goal of the task, the various sub-tasks, and the conditions under which they should be carried out to achieve the goal. Complex tasks are represented as a hierarchy of steps with applicable conditions. Additional information is presented for each step, including potential errors, the probability that the error will occur at the step, the severity of the error, or possible design solutions to reduce the probability of the error occurring.

3.2.1.3 Cognitive Task Analysis

A Cognitive Task Analysis (CTA) attempts to address the underlying mental processes that give rise to errors and complicated decision-making. These are particularly useful when the analysis involves higher level cognitive functions such as decision-making and problem solving.

A CTA involves the following primary steps:

1. A task overview (often taking the form of an operational scenario) is developed that provides a broad overview of the task. This overview includes listing the task steps and identifying the cognitive elements at each step (e.g., decision points).

2. A knowledge audit is performed that surveys the level of expertise required for a task using probing, concrete examples in the applicable operational environment. Expertise is typically qualified by those who possess the ability to:

    a. Diagnose and predict issues in the system before they arise

    b. Develop and know when to apply tricks of the trade

    c. Improvise

    d. Recognize anomalies

    e. Compensate for equipment limitations

3. A simulation interview is conducted that allows the interviewer to probe the cognitive processes of the expert user within the context of a specific scenario. This process helps to better understand the involved cognitive processes within the context of a task. Major events, including judgements, decisions, and difficulties, are recorded from the task scenario.

4. The researcher develops a cognitive demands table by consolidating and synthesizing the information from the previous three steps. The cognitive demands table includes the overall goals, which steps include difficult cognitive elements, why these elements are difficult, common errors, and strategies used to prevent errors and complete task goals (Militello & Hutton, 1998).

3.2.1.4 Goals, Operators, Methods, and Selection Rules Modeling

Goals, Operators, Methods, and Selection Rules (GOMS) is a family of predictive models of human performance that can be used to improve the efficiency of human-system interaction by identifying and eliminating unnecessary user actions. GOMS modeling breaks the task into goals or subgoals (Goals). With the goals and subgoals defined, the next step is to identify the behaviors (physical and cognitive) that the worker uses to complete a subgoal (Operators) and the time taken to complete the subgoal. The researcher then looks for, and identifies, any sequences of commonly occurring operators (Methods) and rules users employ to select among competing methods (Selection Rules).

3.2.2 Cognitive Walkthrough

A Cognitive Walkthrough (CW) is a human factors evaluation exercise that involves a small group of actors evaluating a new design (e.g., system, capability, concept, interface) with a task-oriented focus. Several varieties of CWs exist; however, for the purposes of this document, we suggest having a small group of SMEs in a group setting (facilitated by a researcher) perform and describe a scripted, directed task.

CWs are used to address the following primary questions (Blackmon, et al., 2002):

- Will the user try and achieve the right outcome?
- Will the user notice that the correct action is available?
- Will the user associate the correct action with the outcome they expect to achieve?
- If the correct action is performed, will the user see that progress is being made towards their intended outcome?

In conducting a CW, the researcher first defines the task or tasks that the participants will be expected to carry out. These tasks are often detailed in a descriptive operational scenario that the researcher will guide the participants in a "walking through." Any tasks or functions that can be performed, but are not the focus of the task scenario, are normally not assessed during the process.

The researcher then leads the participants through the scenario as unobtrusively as possible (e.g., introducing the concepts and tasks to be accomplished only). Participants are asked to openly discuss the methods, steps, and actions they would take to achieve the goals of the scenario (e.g., accomplish the defined tasks). Open discourse is encouraged as participants often feed off each other which yields more thorough and rich data. The research team records detailed observations of participant comments (with prior consent recording the session is recommended) for later analysis.

One of the main benefits of CWs are that they are inexpensive and easy to conduct. CWs allow for a concept to be examined from the perspective of the end-user (e.g., Certified Professional Controller (CPC)) and provide SME feedback. CWs do not require a fully developed concept or system to conduct. If used early, CWs can prevent design flaws that can otherwise be avoided with SME input.

3.2.3 Interactive Simulation Testing

As the name suggests, interactive simulations involve a participant interacting with a concept, system, or capability. These simulations are scientifically controlled studies involving end-users engaged in accomplishing a pre-determined task in a simulated operational environment. These simulations allow concepts, systems, and capabilities to be tested in the highest fidelity possible next to actual deployment. They offer researchers and developers the richest, most ecologically valid data possible, and the scientific control used in the simulations allow for the highest level of confidence in any performance related or some other variable of interest (e.g., training requirements, workload, stress, fatigue) results observed. Interactive simulations are cost prohibitive and time-consuming. As a result, they are rarely encouraged early on in any concept development process. In this document, we reference two specific types of interactive simulations for researching the human factors associated with the UAM concept both in the mid- and far-term states: 1) Human-In-The-Loop (HITL), and 2) Human-Over-The-Loop (HOTL) simulations. The two are briefly introduced below. For more complete descriptions readers are referred to the FAA's Systems Engineering Manual.

3.2.3.1 Human-In-The-Loop Simulation

Traditionally, the FAA has conducted HITL simulations where the human participant has complete control over starting or stopping any action performed by a system after receiving a cue. For example, in a simulated ATC environment where an intelligent algorithm optimizes traffic flow by deciding the best aircraft to move from one traffic stream to another will still involve the controller deciding whether to accept the recommendation, and then determine which aircraft to move.

3.2.3.2 Human-Over-The-Loop Simulation

As technology and systems become more highly automated, the expectation is that the human control of the system will be pushed further away from the decision-making process. Humans would still have oversight of these systems but the system would take immediate action and would not require human approval like in an HITL design. In other words, the human agent serves more as a monitor than an active participant in the system. This new type of design is referred to as Human-Over-The-Loop (HOTL).

3.3 Air Traffic Control Human Factors Research Area Considerations

This section discusses the high-level human factors research areas that warrant further investigation to determine any/all impacts of HAVs and UAM operations to ATC. The following subsections illustrate the expected relevance of human factors research areas to a specific subject area. Anticipated relevance is summarized in the tables as Primary (P), Secondary (S), or not relevant (no indicator). Detailed and specific research questions pertaining to these research areas are described in Appendix D.

3.3.1 Introducing HAV Corridors into the NAS

The introduction of HAV Corridors to enable high operational volumes of HAVs operating in this airspace is a unique construct for traditional ATC, where aircraft will be flying in controlled airspace without requiring traditional ATC services for the airspace of operation. The current assumption is ATC will only know the corridor status (e.g., hot, cold) but will not be aware of how many operations are occurring or the positions and speeds of the aircraft within the corridors. In controlled airspace, ATC will deconflict ATM traffic from the HAV Corridors unless the ATM aircraft is corridor-capable and coordinates joining or crossing a corridor in the HAV Ecosystem. Corridor impacts should be prioritized and analyzed for unintended impacts to ATC in the early stages of concept maturation to fully understand their associated air traffic control human factors implications and inform future research efforts (e.g., UAM Corridor design and analysis, UAM conceptual architecture). Research into the air traffic control human factors implications of the introduction of UAM Corridors can provide understanding of their effects generalizable to HAV operational concepts that involve separate traffic management systems for HAVs and normally controlled air traffic.

3.3.1.1 Impact of UAM Corridors on ATC

Establishing UAM Corridors within the NAS introduces several human factors concerns related to ATC. When these UAM Corridors are “hot”, an additional constraint is now imposed on ATC limiting flexibility in an already highly used airspace. The positioning of UAM Corridors has implications for ATC and should consider the potential amount of additional workload experienced by ATC working traditional traffic around UAM Corridors and interactions with current day routes. Research must address how introducing these new structures in proposed locations will impact ATM traffic flow patterns, ATC procedures, and ATC workload in all classes of airspace to better inform UAM Corridor locations. Table 1 indicates relevance of human factors research areas to the impacts of “hot” UAM Corridors on ATC.

Table 1: HF Research Relevance for Impact of UAM Corridors on ATC

Workload	Stress	Information Flow	Automation	Training	Cognitive	Performance	Teamwork	Situational Awareness
P	S	S		S	S	S	S	S

As illustrated above, workload is expected to be the primary ATC human factors area of concern. However, multiple secondary effects and additional air traffic control human factors considerations and impacts also need to be assessed. As UAM Corridors become more complex in structure and design, research must continue to assess future impacts in the mid- and far-terms. These areas of concern will also apply to similar corridor structures supporting other HAV operations. Specific research questions for this area are outlined in Appendix D, questions #1-7.

3.3.1.2 UAM Corridor Status Information Exchanges

As UAM Corridors are incorporated into the NAS, research must address how the status of these UAM Corridors will be communicated between corridor traffic management, ATC, and ATM to maintain shared situational awareness while minimizing impacts on controllers' workload. The method of communication may begin as human-human, but as operations and technologies mature, this information exchange may become more automated and shift to human-machine. Each communications method brings its own set of changes to controller tasks and associated human factors impacts.

As depicted in Table 2, information flow/communication is expected to be the primary focus, but several other secondary human factors considerations will also need investigation for their associated impacts. As an example, most information exchanges will involve some form of cognition (e.g., perception, processing). Specific research questions for this area are outlined in Appendix D, questions #8-12.

Table 2: HF Considerations for UAM Corridor Status Information Exchanges

Workload	Stress	Information Flow	Automation	Training	Cognitive	Performance	Teamwork	Situational Awareness
S	S	**P**	S		S	S		S

3.3.1.3 UAM/ATM Capable Aircraft Joining UAM Corridors

As discussed in UAM ConOps v1.0 and the UAM Use Case document[3], any aircraft meeting the performance requirements of a UAM Corridor may join and continue operations in the UAM Corridor if the UAM operator/Pilot in Command (PIC) has a confirmed UAM Operational Intent through a PSU. All requests to operate within a UAM Corridor are either confirmed or rejected through the PSU/PSU Network. ATC will not have awareness nor the status of requests going to a PSU. If flying in controlled airspace nominally (particularly Class B), the UAM operator/PIC will need or may request (airspace dependent) ATC services to vector towards the confirmed UAM Corridor entry point at the approved time. Research is required to assess the impacts of this additional task on ATC, particularly as the number of requests increases, to determine the operational feasibility of this concept from a workload and communication perspective.

As show in Table 3, this research area touches on all human factors categories but is primarily aimed at addressing how ATC workload will be impacted by nominal requests to join a UAM Corridor and communication problems/information gaps between all actors.

Table 3: HF Considerations for HAVs Joining Corridors

Workload	Stress	Information Flow	Automation	Training	Cognitive	Performance	Teamwork	Situational Awareness
P	S	**P**	S	S	S	S	S	S

Identifying areas unique to entering a UAM Corridor versus how traditional ATM aircraft enter and leave controlled airspace nominally can help inform ATC policies and procedures. Early research will be important to assure concept feasibility of aircraft joining UAM Corridors in the

[3] ANG UAM Use Case Document, 19 November 2020

near-term and as operations mature. Insights into to the human factors effects in this area will also apply to other HAV operations that involve aircraft entering corridors from controlled airspace. Specific research questions for this area are outlined in Appendix D, questions #13-15.

3.3.1.4 HAVs Leaving a UAM Corridor

UAM-capable aircraft are allowed to leave a UAM Corridor as long as all performance and airspace requirements are met for the airspace to be entered. Research is needed to assess the human factors impacts on ATC when HAVs leave a UAM Corridor, in varying numbers and frequencies, under both nominal and off-nominal conditions. While nominal impacts may be minimal in the near-term with low operational volumes, as operations become more mature, the number of requests could significantly increase creating workload and communication challenges for ATC. Increasing the volume of UAM operations in controlled airspace beyond a few flights at a time may exceed a controller's workload capacity and lead to delay or rejection of UAM aircraft access to the airspace.

Assessing and identifying areas to make the transition out of the UAM Corridor normalized to current operations with ATM aircraft should be considered to minimize ATC workload and training issues. If differences exist for how ATC controls ATM aircraft versus UAM aircraft, a controller could perform the wrong action or wrong procedure due to distraction, inattention, inexperience, and other human factors aspects. This issue, termed negative training transfer, has been problematic with aircraft simulator design or procedures not translating to the real-world aircraft in an emergency. In this instance, a controller may use the procedures for ATM aircraft that may be different or not appropriate for UAM aircraft leading to error. The result of this research could have impacts on controller position workload and result in subsequent changes to ATC procedures, which may warrant changes in training for ATC.

Additionally, research on UAM off-nominal events and associated ATC information requirements (e.g., perception, response timing) for UAM-capable aircraft/HAVs unexpectedly exiting a UAM Corridor (e.g., non-conformance, emergency scenarios) needs to be explored with possible automation support tools. Off-nominal situations in controlled airspace can cause controllers to become saturated as their cognitive load exceeds their capabilities to provide services. Automation support tools should be investigated for benefits to ATC situational awareness and cognitive workload. As shown in Table 4, the primary research areas include workload, information flow, and cognitive human factors.

Table 4: HF Considerations for HAVs Leaving a UAM Corridor

Workload	Stress	Information Flow	Automation	Training	Cognitive	Performance	Teamwork	Situational Awareness
P	S	**P**	S	S	**P**	S	S	S

During the early stages of concept maturation, understanding these impacts (both nominally and off-nominally) will help inform the design of UAM Corridors, aircraft capabilities, information requirements, and information exchanges and apply to other HAV operations. Specific research questions for this area are outlined in Appendix D, questions #16-35.

3.3.2 Operations and Procedures

As UAM operations and HAVs integrate into the NAS, research needs to address how ATC operations and procedures with HAVs differ from traditional ATM aircraft. Gaps in current ATC operations and procedures need to be identified to address and recommend changes in policies and procedures. This research includes identifying:

- Current procedures no longer applicable for HAV interactions
- Current training and knowledge gaps
- Compromised situational awareness and subsequent implications when HAVs unexpectedly exit a UAM Corridor
- Communication gaps between ATC and HAVs

Additional research will be needed for contingency management when an aircraft in controlled airspace, not meeting the UAM performance requirements, unexpectedly enters a UAM Corridor and assess proper roles/responsibilities for ATC, the operator/PIC, and the HAV through DAA and/or additional technologies.

The primary research considerations shown in Table 5 include information flow, training, and situational awareness. Specific research questions for this area are outlined in Appendix D, questions #36-43.

Table 5: HF Considerations for Operations and Procedures

Workload	Stress	Information Flow	Automation	Training	Cognitive	Performance	Teamwork	Situational Awareness
		P		**P**	S	S	S	**P**

3.3.3 Information Exchanges Between UAM, ATC, and HAVs

UAM operations will only communicate with ATC during an off-nominal scenario or when requesting to leave a UAM Corridor. The level and timing of required communication with ATC for both scenarios is unknown and airspace dependent. As shown in Table 6, human factors research is necessary to investigate the level of communication required between the UAM operator/PIC/HAV and ATC for impacts primarily in information flow and situational awareness.

Table 6: HF Considerations for Information Exchanges Between UAM, ATC, and HAVs

Workload	Stress	Information Flow	Automation	Training	Cognitive	Performance	Teamwork	Situational Awareness
S	S	**P**	S		S	S		**P**

In the near-term, voice communications will likely be the primary communication method between the UAM operator/PIC and ATC as traditional pilots are expected to be onboard the aircraft. However, as UAM operations mature and the pilot transitions to a remote location with enhanced technology and automation support, effective communication modes and information exchanges between the UAM Ecosystem and ATC (e.g., request exit from UAM Corridor) need to be analyzed. Pilots today communicate with controllers through voice-based radio networks. These communications are not only inefficient, requiring as much as 50% of a controller's time to convey routine information, but the radio frequencies can also only support one conversation at a time and may become saturated at high aircraft volumes. This mode of communication between HAVs and ATC for operating in ATM airspace is likely to change and become more automated as UAM operations and technology become more mature. Understanding the effects of this transition through communications modes on controller performance will help guide decisions on communications in other HAV operations.

Research will address where UAM communications will be present in the ATC facility, and in what format, while being considerate of potential impacts to controller workload and staffing levels. Additional information exchanges, to include the PSU, need to be assessed to determine ATC informational needs to maintain situational awareness of airspace operations and plan accordingly. Specific research questions for this area are outlined in Appendix D, questions #44-49.

3.3.4 Simultaneous Interactions with Varying UAM and HAV Maturity Levels

As UAM operations gradually move towards a mature state and HAV capabilities increase, ATC interactions with varying levels of aircraft maturity may impact performance. A concern is the interaction among human pilots, operators, or controllers and increasingly automated systems. The introduction of dual HAV/ATM capable aircraft will bring wide variability and mixed performance of automation, aircraft capabilities, and equipage that will create challenges for ATC. Understanding the human factors implications when ATC must simultaneously handle aircraft with onboard pilots, remote pilots, pilots with reduced training, and highly automated pilots will be important throughout concept maturation. UAM pilot capabilities and levels of training may vary between airspace users creating additional complexities for interaction.

Safe airspace integration of HAVs and automated systems will require interoperability including the vehicles and systems of existing airspace users and the service provider. More generally, interoperability will be essential for a service-oriented data exchange and the harmonization of different technologies in various states of maturity. At a minimum, standards must be developed for the data exchange and Communications, Navigation, and Surveillance (CNS)/ATC services. In addition, protocols may need to be developed to ensure the integrity, timeliness, and consistent understanding of the information being exchanged by different vehicles, systems, and users.

As shown in Table 7, human factors research must investigate and understand the impacts of these simultaneous information exchanges and associated impacts to performance throughout concept maturation. Research will be needed to ensure the safe integration of HAVs into the airspace system at varying stages of maturity. Specific research questions for this area are outlined in Appendix D, questions #50 & 51.

Table 7: HF Considerations for Interacting with Varying UAM and HAV Maturity Levels

Workload	Stress	Information Flow	Automation	Training	Cognitive	Performance	Teamwork	Situational Awareness
S	S	**P**	S	S	**S**	**P**	S	S

4 Notional Timeline and Sequencing of Events

The notional research sequence of events shows the suggested timeline for addressing the research questions to align with the maturity states as outlined in Table D1. Research areas in the near-term represent foundational HF research areas and questions that need to be addressed early on in concept development and design. This will better inform the impacts and feasibility of UAM Corridors, UAM Corridor Design and Analysis, and UAM Systems Architecture with respect to their impacts on ATC which can then be used to infer impacts that can be expected more generally with respect to HAV operations. The questions in the near-term will set the stage for additional research questions and outcomes to then inform and apply to the mid-term and far-term research questions. As other HAV operations move toward integration into the NAS, the same evolution can be expected for them as well.

Throughout research progression, some research questions may need to be revisited and re-assessed to ensure their conclusions have not changed as operational tempo and automation levels increase with maturing operational states. The evolution of research questions and revisiting of previous questions is depicted with a two-way arrow in Figure 2.

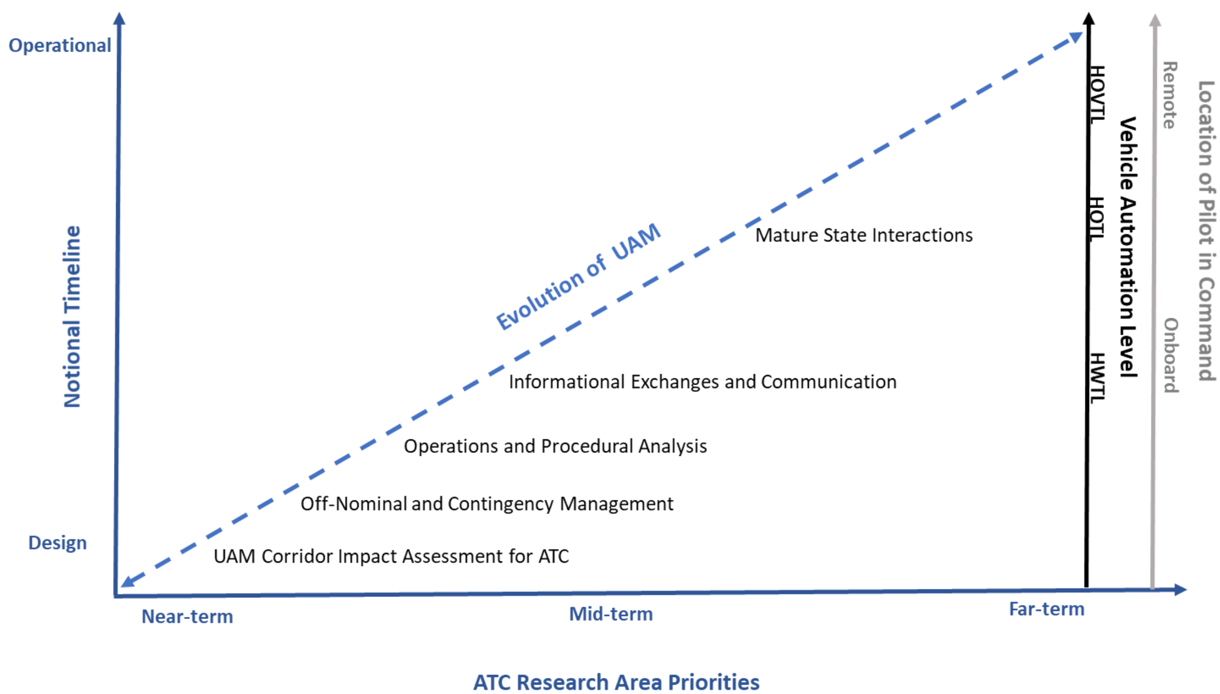

Figure 2: Research Question Timeline

5 Conclusion/Next Steps

As illustrated by the UAM ConOps, implementation of HAVs into the NAS will be an evolutionary approach starting with low-complexity, low-operational tempo operations with a pilot onboard building towards an environment of higher operational tempo, with possible changes to airspace structure, and remotely piloted aircraft with HOVTL automated systems allowing more advanced interactions with the ATM environment. As the concepts evolve and new technologies are developed, human factors research must be conducted early and often to ensure efficient integration into the NAS with minimal disruptions in all phases of design and implementation.

Human factors research requires the inclusion of ATC SMEs to ensure proper understanding of the operational environment, procedures, assumptions, and constraints when interacting with HAVs. Research should begin with tabletop exercises (e.g., Task Analysis, Cognitive Walkthrough) before determining if specialized equipment or expensive simulations are needed or warranted. These research efforts will inform future concept development, design, and information exchanges from an early stage and provide the foundations for safely incorporating HAVs while minimizing the impact to ATC and ATM operations.

The next steps to implement this research plan in the near-term include developing specific and detailed research designs for the research questions proposed in this document. As outlined in Figure 2, the focus should begin with UAM Corridor impacts to ATC followed by off-nominal and contingency management, and operations and procedures. The specific research designs should begin with tabletop exercises utilizing ATC SMEs to better understand research question dependencies and gather data before moving into more extensive and structured simulations (e.g., HITL). As more information and data become available for these operations through initial research efforts and concept maturation, research will likely evolve to incorporate more simulation-based research designs in the mid-term and far-terms.

Appendix A References

Blackmon, M. H., Polson, P. G., Kitajima, M., & Lewis, C. (2002). Cognitive Walkthrough for the Web. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems Changing Our World, Changing Ourselves - CHI '02*, 1. https://doi.org/10.1145/503376.503459

Endsley, M. R. (1995). Toward a Theory of Situation Awareness in Dynamic Systems. *Human Factors*, *37*(1), 32-64.

Federal Aviation Administration. (2020). *Urban Air Mobility (UAM) Concept of Operations v1.0.* Washington, DC: Federal Aviation Administration

Federal Aviation Administration. (2020). *Urban Air Mobility (UAM) Use Case Document v1.0.* Washington, DC: Federal Aviation Administration

Fernandes, A., & Braarud, P. O. (2015). Exploring Measures of Workload, Situation Awareness, and Task Performance in the Main Control Room. *Procedia Manufacturing*, *3*, 1281–1288. https://doi.org/10.1016/j.promfg.2015.07.273

Militello, L. & Hutton, R. (1998). Applied Cognitive Task Analysis (ACTA): A Practitioner's Toolkit for Understanding Cognitive Task Demands. *Ergonomics.* 41. 1618-41. https://doi.org/10.1080/001401398186108

Nzelu, O. (2018). Human Factors: The Dirty Dozen in CTG Misinterpretation. *Global Journal of Reproductive Medicine*, *6*(2), 1. https://doi.org/10.19080/gjorm.2018.06.555683

Appendix B Acronyms

Acronym	Definition
ADS-B	Automatic Dependence Surveillance-Broadcast
AGL	Above Ground Level
ANG-C1	FAA Organization – NexGen Human Factors Division
ATC	Air Traffic Control
ATM	Air Traffic Management
CNS	Communication, Navigations, and Surveillance
ConOps	Concept of Operations
CPC	Certified Professional Controller
CTA	Cognitive Task Analysis
DAA	Detect and Avoid
eVTOL	Electric Vertical Take Off and Landing
FAA	Federal Aviation Administration
GOMS	Goals, Operators, Methods, and Selection Rules
HAV	Highly Automated Vehicle
HF	Human Factors
HFACS	Human Factors Analysis and Classification System
HITL	Human-In-The-Loop
HOTL	Human-On-The-Loop
HOVTL	Human-Over-The-Loop
HTA	Hierarchical Task Analysis
HWTL	Human-Within-The-Loop
ICAO	International Civil Aviation Organization
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
PIC	Pilot in Command
PSU	Provider of Services for UAM
RADAR	Radio Detection and Ranging
RPIC	Remote Pilot in Command
SME	Subject Matter Expert
TFR	Temporary Flight Restriction
UAM	Urban Air Mobility
UAS	Unmanned Aircraft System

Appendix C Glossary

Term	Definition
Air Traffic Management	The dynamic, integrated management of air traffic and airspace including air traffic services, airspace management and air traffic flow management — safely, economically, and efficiently — through the provision of facilities and seamless services in collaboration with all parties and involving airborne and ground-based functions. (Source: International Civil Aviation Organization (ICAO) Doc 4444 PANS-ATM)
Cognition	Human perception and cognitive processes relevant to human performance.
Constraint	An impact to the capacity of a resource. Constraints can be natural (e.g., weather), circumstantial (e.g., runway construction), or intentional (e.g., Temporary Flight Restriction (TFR)).
Highly Automated Vehicle (HAV)	A UAM-capable aircraft with increased automation capabilities from those of traditional aircraft. These vehicles are not autonomous but will reach a state of highly automation functioning with a HOVTL design.
Human Factors	Environmental, organizational and job factors, and human and individual characteristics which influence behavior at work in a way which can affect health and safety. (Source: World Health Organization) Involves the design of technologies and work environments to be compatible with human capabilities and limitations.
Human On-The-Loop (HOTL)	Human supervisory control of the automation (systems) where the human actively monitors the systems and can take full control when required or desired.
Human Over-The-Loop (HOVTL)	Human informed, or engaged, by the automation (system) to take actions. Human passively monitors the systems and is informed by automation if, and what, action is required. Human is engaged by the automation either for exceptions that are not reconcilable or as part of rule set escalation.
Human Within-The Loop (HWTL)	Human is always in direct control of the automation (systems).

Term	Definition
Performance-Based Errors	Errors in performance stemming from skill, decision, or perception. (Source: Human Factors Analysis and Classification System (HFACS)) - Skill-Based Errors occur in the operator's execution of a routine, highly practiced task relating to procedure, training or proficiency and result in an unsafe situation. - Decision Errors occur when the behaviors or actions of the operators proceed as intended yet the chosen plan proves inadequate to achieve the desired end-state and results in an unsafe situation. - Perceptual Errors occur when an operator's sensory input is degraded and a decision is made based upon faulty information.
Provider of Services for UAM (PSU)	An entity that assists UAM operators with meeting UAM operational requirements to enable safe and efficient use of UAM Corridors and vertiports. This service provider shares operational data with stakeholders and confirms flight intent.
PSU Network	A collection of PSUs with access to each PSU's data for use and sharing with their subscribers.
Situational Awareness	The *perception* of the elements in the environment within a volume of time and space, the *comprehension* of their meaning, and a *projection* of their status in the near future. (Source: Endsley, 1995)
Strategic Deconfliction	Deconfliction of UAM Operational Intent via advanced planning and information exchange.
Stress	The subconscious response to the demands placed upon us. Stress can lead to errors when excessive as stress acts as a distraction and reduces concentration levels when performing complex tasks. (Source: Nzelu, 2018)
UAM Corridor	An airspace volume defining a three-dimensional route segment with performance requirements to operate within or cross where tactical ATC separation services are not provided.
UAM Operation	The transport of people or goods from one vertiport to another using UAM Corridors.

Term	Definition
UAM Operational Intent	Operation specific information including, but not limited to, UAM operation identification, the intended UAM Corridor(s), vertiports, and key operational event times (e.g., departure, arrival) of the UAM operation.
UAM Operator	The person or entity responsible for the overall management of an UAM operation; represents the organization that is executing the operation.
Vertiport	A location from which UAM flights arrive and depart. Vertiport is used explicitly when the context indicates functionality to support UAM operations that is not present in current NAS operations.
Workload	Workload, more specifically cognitive workload, refers to the amount of work that an individual can perform at a certain time, or more specifically, the amount information an individual can process or the mental effort required to complete a task. Workload is commonly self-evaluated, reflecting an individual perception of a multidimensional concept, covering aspects related with mental and physical effort, frustration, or time constraints that go beyond the objective task difficulty and demands. (Source: Fernandes & Braarud, 2015)

Appendix D Recommendations for Specific Human Factors Research Questions

As described in Section 3, Table D1 lists recommended research questions that correspond to the human factors research areas between ATC, ATM, and UAM/HAVs. While the focus of these questions is on UAM operations, many of these research questions are applicable and transferrable to more extensive HAV operations. This list is meant to guide researchers in key areas of human factors concern but does not prescribe any one specific research design. These research questions are part of an evolving concept. These questions may need to be re-visited throughout maturing states to ensure previous findings have remained unchanged as UAM moves towards a mature state, and additional questions may be warranted as a result of research outcomes.

Definitions

Independent Variable – Factors which are manipulated or changed in the research question that are assumed to have direct impacts on the outcome. Other variables not listed may be warranted per the proposed research design.

Dependent Variable – The measure that is expected to show an effect from a change in one or more independent variables.

Method – The human factors methodology recommended for inclusion in the research design. This section is not prescriptive as others may be used in conjunction with, or as part of, a research progression. The aim is to begin research with low-cost methodologies (e.g., Cognitive Walkthroughs) before utilizing high-cost interactive simulations (e.g., HITL).

Priority – Defined as the priority to support UAM concept maturation.

- Near-term – These questions are aimed to inform the early/initial stages of UAM operations and concepts, UAM Corridor design, and UAM system architecture. The pilot will be onboard supported by HWTL automation. Additionally, current policies and procedures that may need modification/change as a result of UAM operations should also be identified in this stage due to the length of implementation time.

- Mid-term – These questions are aimed to inform the impacts of increasing UAM operations beyond initial operations and associated impact to ATC. The pilot may be onboard or remote supported by HOTL automation.

- Far-term – These questions are aimed to inform the impacts of a mature state of UAM operations, HOVTL automation, and associated impact to ATC. The pilot is expected to be remote supported by HOVTL automation.

Table D1: Recommended Human Factors Research Questions for ATC, UAM, and HAVs

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.1.1	1. Does ATC workload and stress increase by introducing initial UAM Corridors and controlling ATM aircraft in airspace containing "hot" UAM Corridors? If so, how much? How will ATC workload/stress change with increasing UAM Corridors with added complexities (e.g., intersecting) and as UAM operations mature?	Classes of airspace ATM surrounding traffic levels Staffing levels	Controller workload Situation awareness	Task Analysis	Near-term
3.3.1.1	2. What percentage of ATC voice communication increases as a result of HAV interactions? Is frequency congestion an issue?	Classes of airspace ATM surrounding traffic levels Staffing levels	Controller workload Time to completion	Simulation	Mid-term
3.3.1.1	3. Are traditional ATM services affected by the introduction of UAM Corridors? If so, which?	Classes of airspace ATM surrounding traffic levels Staffing levels	Controller workload Situation awareness Working memory demand Traffic throughput	CW	Near-term
3.3.1.1	4. Will the order of service priorities be affected or altered due to UAM Corridors? Is the current model of "First Come, First Served" altered in any way by the introduction of UAM?	Classes of airspace ATM surrounding traffic levels Staffing levels	Controller workload Situation awareness Traffic throughput	CW	Near-term
3.3.1.1	5. Is airspace design and balance affected by the introduction of UAM Corridors? Are sectors without UAM Corridors affected by being adjacent to a sector with UAM Corridors? Is a dedicated UAM monitor or controller (e.g., helicopter position) a viable construct?	Classes of airspace ATM surrounding traffic levels Staffing levels	Controller workload Situation awareness	CW	Near-term

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.1.1	6. What frequency of performance-based errors occur for ATC when UAM Corridors are “hot” compared to when they are “cold” (e.g., unaware of status and inadvertently cleared an aircraft through a hot UAM Corridor)? Does maintaining awareness result in distractions or cognitive overload?	Classes of airspace ATM surrounding traffic levels Staffing levels	Situation awareness Error rate	Task Analysis	Near-term
3.3.1.1	7. Does the toggling of UAM Corridor status (e.g., hot, cold) negatively affect work position balance or ATC situational awareness?	Classes of airspace ATM surrounding traffic levels Staffing levels	Situation awareness Working memory demand Controller workload	CW	Near-term
3.3.1.2	8. How will HAVs communicate with ATC through varying stages of maturity when requesting to leave the UAM Corridor or during off-nominal scenarios (e.g., voice, data link, other digital/automated system)? What method is the most effective for ATC in relaying critical information and maintaining situational awareness?	Classes of airspace ATM surrounding traffic levels Staffing levels	Controller workload Time to completion Situation awareness	HITL	Mid-term
3.3.1.2	9. What frequency/rate, if at all, do ATM pilots request the status of UAM Corridors (e.g., once/30 min, once/hr.)? Does ATC perceive that this communication adds significant workload to their current operations? How will ATM aircraft be made aware of UAM Corridor status? (e.g., charting, request for information)	Classes of airspace ATM surrounding traffic levels Staffing levels	Controller workload Working memory demand Situation awareness	HITL	Mid-term
3.3.1.2	10. As the pilot shifts to a remote location, what level of communication (if any) is needed and under what conditions will communication be needed? When necessary, how will Remote Pilots in Command (RPICs) and ATC communicate with each other (e.g., voice, automated system)? How is this different than traditional ATM pilots? What is the most effective communication method?	Classes of airspace ATM surrounding traffic levels Staffing levels	Controller workload Time to completion Situation awareness	HITL HOVTL	Mid/Far-term

Sectio n	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.1.2	11. Is ATC constantly aware of UAM Corridor status? How is UAM Corridor status communicated during shift turnovers? What is the error rate in communicating the UAM Corridor status (e.g., controller forgot to brief the status during the shift changeover)? Did the error compromise safety at any point?	Classes of airspace ATM surrounding traffic levels Staffing levels	Situation awareness Working memory demand Error rate	CW	Near-term
3.3.1.2	12. What is the process for ATC notification, display depiction, and status of when UAM Corridors are hot? Is this similar or different than current ATC processes?	Classes of airspace ATM surrounding traffic levels Staffing levels	Situation awareness Working memory demand	CW	Near-term
3.3.1.3	13. How will the cancellation and timing of a UAM Operational Intent by the PSU for UAM-capable aircraft/HAVs entering a UAM Corridor impact ATC workload ratings (e.g., if cancelled, the aircraft must remain in the ATM environment)? What is the process/procedure for ATC when a UAM Operational Intent cancellation occurs between the PIC/HAV and PSU (e.g., delay in cancellation results in a holding pattern outside the UAM Corridor until an amended confirmed UAM Operational Intent is received)?	Classes of airspace ATM surrounding traffic levels Shift characteristics Number of HAVs requesting entry into UAM Corridor from ATC Frequency of request	Controller workload Situation awareness Working memory demand Time to completion	Task Analysis	Near-term
3.3.1.3	14. Does controlling UAM-capable aircraft/HAVs towards the confirmed UAM Operational Intent entry point result in other tasks being neglected due to increased workload? If so, which tasks and how frequently?	Classes of airspace ATM surrounding traffic levels Shift characteristics Number of HAVs requesting entry into UAM Corridor from ATC Frequency of request	Controller workload Situation awareness Working memory demand	Task Analysis	Near-term

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.1.3	15. How much workload (e.g., voice communication, vectoring to a specific point on the UAM Corridor) is added to ATC when handling requests to join a UAM Corridor?	Classes of airspace ATM surrounding traffic levels Shift characteristics Number of HAVs requesting entry into UAM Corridor from ATC Frequency of request	Controller workload Situation awareness Working memory demand	Task Analysis	Near-term
3.3.1.4	16. How many times (frequency) did the controller feel overloaded when dealing with an off-nominal HAV scenario? How does this compare to dealing with ATM emergency scenarios?	Classes of airspace ATM surrounding traffic levels Shift characteristics Number of HAVs exiting UAM Corridor Frequency of off-nominal exits ATC knowledge of operations within the UAM Corridor Time of notification Staffing levels	Controller workload Working memory demand	Task Analysis	Near-term

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.1.4	17. What was the overall perceived workload and stress levels of ATC responding to an off-nominal HAV? How does this compare to dealing with ATM emergency scenarios?	Classes of airspace ATM surrounding traffic levels Shift characteristics Number of HAVs exiting UAM Corridor Frequency of off-nominal exits ATC knowledge of operations within the UAM Corridor Time of notification Staffing levels	Controller workload Situation awareness	Task Analysis	Near-term
3.3.1.4	18. What was the stress and workload rating of ATC when notification occurred *after* the HAV exited the UAM Corridor? Especially in Class B/C (with Radio Detection and Ranging (RADAR) surveillance) airspace.	Classes of airspace ATM surrounding traffic levels Shift characteristics Number of HAVs exiting UAM Corridor Frequency of off-nominal exits ATC knowledge of operations within the UAM Corridor Time of notification Staffing levels	Controller workload Situation awareness	Task Analysis	Near-term

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.1.4	19. What was the stress and workload rating for ATC when notification occurred *before* the HAV exited the UAM Corridor at various time intervals?	Classes of airspace ATM surrounding traffic levels Shift characteristics Number of HAVs exiting UAM Corridor Frequency of off-nominal exits ATC knowledge of operations within the UAM Corridor Time of notification Staffing levels	Controller workload Situation awareness	Task Analysis	Near-term
3.3.1.4	20. How many off-nominal HAVs can be managed by ATC before there is significant increase in perceived stress and workload? What is the effect or impact to attention devoted to ATM services?	Classes of airspace ATM surrounding traffic levels Shift characteristics Number of HAVs exiting UAM Corridor Frequency of off-nominal exits ATC knowledge of operations within the UAM Corridor Time of notification Staffing levels	Controller workload Situation awareness Working memory demand	HITL	Mid-term

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.1.4	21. What type of off-nominal event resulted in the highest levels of perceived workload and stress (e.g., emergency, non-conformance, lost link)?	Classes of airspace ATM surrounding traffic levels Shift characteristics Number of HAVs exiting UAM Corridor Frequency of off-nominal exits ATC knowledge of operations within the UAM Corridor Time of notification Staffing levels	Controller workload Working memory demand Situation awareness	Task Analysis	Near-term

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.1.4	22. How long does it take for ATC to become aware of an off-nominal HAV? Is there informational latency associated with off-nominal events and ATC notification? How does this differ from ATM?	Classes of airspace ATM surrounding traffic levels Shift characteristics ATC workload Number of HAVs exiting UAM Corridor Frequency of off-nominal exits ATC knowledge of operations within the UAM Corridor Type of alert Display of HAVs on ATC interfaces	Time to completion Situation awareness Working memory demand	CW	Near-term

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.1.4	23. How long does it take for ATC to respond to an off-nominal HAV from start to finish? How does this differ from ATM emergencies?	Classes of airspace ATM surrounding traffic levels Shift characteristics ATC workload Number of HAVs exiting UAM Corridor Frequency of off-nominal exits ATC knowledge of operations within the UAM Corridor Type of alert Display of HAVs on ATC interfaces	Time to completion Controller workload Working memory demand Situation awareness	CW	Near-term

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.1.4	24. Is there any point in which responding to off-nominal HAVs compromise safety of other ATM aircraft?	Classes of airspace ATM surrounding traffic levels Shift characteristics ATC workload Number of HAVs exiting UAM Corridor Frequency of off-nominal exits ATC knowledge of operations within the UAM Corridor Type of alert Display of HAVs on ATC interfaces	Controller workload Situation awareness Error rate	CW	Near-term

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.1.4	25. What distractions hinder ATC awareness of off-nominal HAVs?	Classes of airspace ATM surrounding traffic levels Shift characteristics ATC workload Number of HAVs exiting UAM Corridor Frequency of off-nominal exits ATC knowledge of operations within the UAM Corridor Type of alert Display of HAVs on ATC interfaces	Situation awareness Working memory demand Time to completion	CW	Near-term

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.1.4	26. How long is attention diverted away from ATM aircraft to resolve HAV off-nominal scenarios? Is this comparable to ATM emergencies?	Classes of airspace ATM surrounding traffic levels Shift characteristics ATC workload Number of HAVs exiting UAM Corridor Frequency of off-nominal exits ATC knowledge of operations within the UAM Corridor Type of alert Display of HAVs on ATC interfaces	Situation awareness Time to completion	HITL	Mid-term

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.1.4	27. What visual display attributes, if any, improve ATC awareness of off-nominal HAVs (e.g., identical to ATM, different color, flashing icon)?	Classes of airspace ATM surrounding traffic levels Shift characteristics ATC workload Number of HAVs exiting UAM Corridor Frequency of off-nominal exits ATC knowledge of operations within the UAM Corridor Type of alert Display of HAVs on ATC interfaces	Controller workload Working memory demand Situation awareness	CW HITL	Near/Mid-term

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.1.4	28. Does an auditory alert aid in off-nominal awareness? Or is it a distraction?	Classes of airspace ATM surrounding traffic levels Shift characteristics ATC workload Number of HAVs exiting UAM Corridor Frequency of off-nominal exits ATC knowledge of operations within the UAM Corridor Type of alert Display of HAVs on ATC interfaces	Situation awareness Time to completion Controller workload	CW	Near-term
3.3.1.4	29. How many HAVs nominally leaving a UAM Corridor can be managed by ATC before there is a significant increase in perceived stress and workload?	Classes of airspace ATM surrounding traffic levels Shift characteristics ATC knowledge of operations within the UAM Corridor Frequency of requests Staffing levels	Controller workload Situation awareness Working memory demand	CW	Near-term

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.1.4	30. How many times did ATC feel overloaded when dealing with requests to leave a UAM Corridor?	Classes of airspace ATM surrounding traffic levels Shift characteristics ATC knowledge of operations within the UAM Corridor Frequency of requests Staffing levels	Controller workload Situation awareness Working memory demand	Task Analysis	Near-term
3.3.1.4	31. What procedures are different when HAVs leave a UAM Corridor versus when ATM aircraft request clearance into controlled airspace?	Classes of airspace ATM surrounding traffic levels Shift characteristics ATC knowledge of operations within the UAM Corridor Frequency of requests Staffing levels	Situation awareness Working memory demand	Task Analysis	Near-term
3.3.1.4	32. How often does ATC receive requests and respond to requests to leave a UAM Corridor during a given shift?	Classes of airspace ATM surrounding traffic levels Shift characteristics ATC knowledge of operations within the UAM Corridor Frequency of requests Staffing levels	Controller workload	HITL (informed by field study)	Mid-term

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.1.4	33. Is there a negative effect of allowing HAVs to leave a UAM Corridor with the amount of ATM aircraft authorized to enter controlled airspace? What is the impact to surrounding airspace (adjacent sectors)?	Classes of airspace ATM surrounding traffic levels Shift characteristics ATC knowledge of operations within the UAM Corridor Frequency of requests Staffing levels	Controller workload Situation awareness	CW	Near-term
3.3.1.4	34. Do UAM Corridor exit authorizations (i.e., entry into controlled airspace) result in other tasks being neglected due to increased workload? If so, which tasks and how frequently?	Classes of airspace ATM surrounding traffic levels Shift characteristics ATC knowledge of operations within the UAM Corridor Frequency of requests Staffing levels	Controller workload Working memory demand Error rate	CW	Near-term
3.3.2	35. What information does ATC need about HAV performance capabilities to effectively control and issue instructions (e.g., climb rate/response to speed adjustments, performance envelope)? What are the knowledge gaps?	Classes of airspace ATC experience level Type of HAV Staffing levels	Situation awareness	CW	Near-term

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.2	36. What procedures/actions do controllers take, if any, when an ATM aircraft (not UAM-capable) enters a UAM Corridor? How is this same/different from ATM entering an unauthorized area?	Classes of airspace ATC experience level Type of HAV Staffing levels	Situation awareness Controller workload	Task Analysis	Near-term
3.3.2	37. What is the impact to ATC when an ATM aircraft receiving ATC services enters, or is predicted to enter, a hot UAM Corridor without meeting UAM participation requirements?	Classes of airspace ATM surrounding traffic levels Shift characteristics Number of HAVs requesting entry into UAM Corridor from ATC Frequency of request	Situation awareness Controller workload Time to completion	HITL HOVTL	Mid-term
3.3.2	38. What procedures/contingencies are in place for HAV off-nominal events? How is this different from ATM emergencies?	Classes of airspace ATC experience level Type of HAV Staffing levels	Controller workload Situation awareness	CW	Near-term
3.3.2	39. What current policies/procedures need to evolve as a result of UAM Corridors? What needs to evolve as a result of HAV capabilities?	Classes of airspace ATC experience level Type of HAV Staffing levels	Controller workload Situation awareness	CW	Near-term
3.3.2	40. How frequently will ATC need training to stay up-to-date on varying HAV capabilities and as operations/vehicle types mature? What type of training will be the most effective?	Classes of airspace ATC experience level Type of HAV Staffing levels	Situation awareness	CW	Mid-term

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.2	41. Is the current ATC staffing model appropriate with the introduction of UAM and HAVs (e.g., respond to off-nominal events)? At what point in UAM maturity will the staffing model need to evolve to accommodate increasing UAM operations occurring outside a UAM Corridor (e.g., off-nominal events, exiting a UAM Corridor)?	Classes of airspace ATC experience level Type of HAV Staffing levels	Controller workload Working memory demand Traffic throughput	CW	Mid-term
3.3.2	42. What is the error rate in ATC procedures for joining/leaving the UAM Corridor? What type of error and what is the severity of the error? How does the PSU account for any ATC procedural error?	Classes of airspace ATC experience level Type of HAV Staffing levels	Error rate Controller workload Situation awareness	Task Analysis	Near-term
3.3.2	43. What procedures will be in place if the confirmed UAM Operational Intent “window” is missed and ATC needs to continue controlling the aircraft (e.g., holding pattern procedures)?	Classes of airspace ATC experience level Type of HAV Staffing levels	Controller workload Situation awareness	Task Analysis	Near-term
3.3.3	44. What is the latency of the PSU in receiving requests to operate within a UAM Corridor and confirming UAM Operational Intent?	Classes of airspace Speed of information exchange Communication modes	Time to completion Situation awareness	Computer modeling and simulation	Near-term
3.3.3	45. Which communication method (e.g., voice, data link, other digital) provides the most efficient mode of communication and information flow between ATC and HAVs?	Classes of airspace Speed of information exchange Communication modes	Time to completion Controller workload	CW HITL	Near/Mid-term
3.3.3	46. What is the time interval (measurement) between when HAVs request entry/exit/cross the UAM Corridor, a PSU confirms/rejects a UAM Operational Intent, the PIC/RPIC contacts ATC, and ATC responds to such requests?	Classes of airspace Speed of information exchange Communication modes	Time to completion Controller workload Situation awareness	HITL	Mid-term

Section	Research Question	Independent Variables	Dependent Variables	Method (s)	Priority
3.3.3	47. Does early notification from the PSU to ATC aid in situational awareness when off-nominal events occur that are expected to exit the UAM Corridor? If so, can this notification be accomplished with existing ATC technology/displays? Is there latency in this notification process?	Classes of airspace Speed of information exchange Communication modes	Situation awareness Controller workload	HOVTL	Mid-term
3.3.3	48. How soon (time interval) does ATC need to know when the PIC's "plan" for a confirmed UAM Operational Intent didn't work and is expected to remain in ATM airspace?	Classes of airspace Speed of information exchange Communication modes	Time to completion Situation awareness Controller workload	CW	Near-term
3.3.3	49. Is airspace and situational awareness impacted (positively or negatively) for ATC through knowledge of the number of UAM operations occurring within a UAM Corridor? Does this have impacts on resource management (number of controllers on shift) with demand and capacity of off-nominal events?	Classes of airspace Speed of information exchange Communication modes	Situation awareness Controller workload Working memory demand	CW	Near-term
3.3.4	50. How many and what type of errors did ATC make while simultaneously controlling aircraft and HAVs in varying states of maturity?	Classes of airspace Maturity of HAV Communication modes	Error rate Situation awareness	HITL	Far-term
3.3.4	51. Is the type of communication the same in all stages of maturity? Is communication more automated in some HAVs? How do the differences impact communication and situational awareness for ATC?	Classes of airspace Maturity of HAV Communication modes	Controller workload Situation awareness	HITL HOVTL	Far-term