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NASA Air Traffic Management – eXploration (ATM-X) Insight Assessment

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This report is available in electronic form at

http://

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1 List of Acronyms

Acronym	Definition
AAM	Advanced Air Mobility
AEDT	Aviation Environmental Design Tool
AI	Artificial Intelligence
ANSP	Air Navigation Service Provider
ASDE-X	Airport Surface Detection Equipment – Model X
ATC	Air Traffic Control
ATM	Air Traffic Management
ATM-X	Air Traffic Management – Exploration
CFD	Computational Fluid Dynamics
ConOps	Concept of Operations
CTOP	Collaborative Trajectory Option Program
DNL	Day-night average sound level
eVTOL	Electric Vertical Takeoff and Landing
FAA	Federal Aviation Administration
FATO	Final Approach and Takeoff Area
FCA	Flow Constrained Area
FOD	Foreign Object Debris
FY	Fiscal Year
GHG	Greenhouse Gas
HITL	Human In The Loop
HSI	Human Systems Integration
IA	Insight Assessment
IDM	Integrated Demand Management
IDO	Increasing Diverse Operations
IR	Insight Review
MIT	Massachusetts Institute of Technology
ML	Machine Learning
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NE	Northeast
PBN	Performance Based Navigation
SME	Subject Matter Expert
TAPPR	Terminal Area Parallel Procedures Research
TARGETS	Terminal Area Route Generation Evaluation, and Traffic Simulation
TBFM	Time Based Flow Management
TBO	Trajectory Based Operations
TCAS	Traffic Collision Avoidance System
TFDM	Terminal Flight Data Manager
TFMS	Traffic Flow Management System
TOS	Trajectory Option Set
TSA	Transportation Security Administration
TSAFE	Tactical Separation Assured Flight Environment
UAM	Urban Air Mobility
UAS	Unmanned Aircraft System
UCAT	UAM Coordination and Assessment Team
UTM	UAS Traffic Management

Acronym	Definition
VFR/IFR	Visual and Instrument Flight Rules
VTOL	Vertical Takeoff and Landing
WTO	Weather Tolerant Operations

2 Executive Summary

The focus of this final Air Traffic Management – eXploration (ATM-X) Insight Assessment (IA) report is to summarize key findings, lessons learned, gaps, and shortfalls from 2018 to 2019 National Aeronautics and Space Administration (NASA) ATM-X research and to share the outcomes from National Airspace System (NAS) stakeholder discussions with the broader community. This report was generated from a comprehensive review of 25 NASA ATM-X research papers and augmented by interviews with 23 NASA researchers as well as three virtual seminars discussing the project findings and priorities with 47 NAS stakeholders. While these papers cover a wide range of relevant topics, they only represent a small portion of the vast amount of ongoing research in this rapidly evolving area by industry, academia, and other agencies. The research summary described here could be further refined and expanded by reviewing additional studies.

During Phase 1, the team synthesized 15 research publications from 2018, focused on the current day problems with flow management and initial Urban Air Mobility (UAM) operations. In addition, the team conducted expert interviews with NASA subject matter experts (SMEs) culminating in the first Insight Assessment Report (IA1). Findings highlighted that current Air Traffic Control (ATC), Air Traffic Management (ATM) procedures, and airport infrastructure can potentially accommodate the initial demand for Vertical Takeoff and Landing (VTOL) operations related to UAM. However, more research is necessary to determine the resources required to reduce controller workload and determine how to safely integrate automation systems needed for UAM operation into the current air traffic system used for commercial fixed-wing operations. New metrics are needed to accurately measure the successes and shortfalls of new entrants and help make accurate corrections to ensure optimum success, growth, NAS integration, and public acceptance. Similarly, more research needs to focus on the applicability of ATM tools such as Time-Based Flow Management (TBFM), Traffic Flow Management System (TFMS), Collaborative Trajectory Option Program (CTOP), or surface movement surveillance such as Airport Surface Detection Equipment (ASDE-X) to support UAM integration.

Phase 2 consisted of a literature review and NASA SME interviews on 10 additional research papers from 2019. Four traditional operations papers described concepts including route automation, metrics, and flow management. The remaining six were UAM literature focused on noise modeling, traffic separation and collision avoidance, scheduling, flow management, and human factors. The Phase 2 research findings, culminated in the second Insight Assessment Report (IA2), affirmed the potential for successful integration of UAM into the NAS while identifying key challenges facing full-scale adoption. Known gaps in vehicle capabilities, routing, weather tolerant operations (WTO), noise mitigation, routing, scheduling of operations, and the role of controllers in managing UAM operations still need to be further researched; however, the current airspace can likely accommodate these initial operations.

In Phase 3, three virtual Insight Review (IR) seminars were conducted with participants from diverse disciplines relating to the NAS. Discussion focused on understanding the key findings, gaps, and future research areas identified in IA1 and IA2. Discussions further investigated findings and gaps from NASA research and helped to prioritize future research for ATM-X. Phase 3 highlighted separation standards, communication frameworks, public perception due to aircraft noise, weather impacts, and safety and emergency protocol as obstacles to UAM integration and large-scale Advanced Air Mobility (AAM) operations. Future research must consider these barriers to implementation and scaling to accurately refine the concept of operations (ConOps) for vehicle configuration and air and ground operations. Existing mission planning and scheduling software with contemporary UAS Traffic Management (UTM) constraints and autonomous inputs can help operators manage the airspace. However, vehicle capabilities, safety, and public perception must first be characterized and addressed.

3 Background

The NASA ATM-X IA project focuses on exploring the transformation of the NAS and aims to identify approaches to provide safe, secure, and equitable access to the airspace for all users. The ATM-X program enables the increased use of user and third-party services to support innovation and scalability. To facilitate the timely dissemination of ATM-X research findings and collect feedback from the broader community for the ATM-X program, the Booz Allen team conducted an ATM-X IA. The goal of this ATM-X IA project was to summarize findings, characterize gaps and shortfalls, and share lessons learned and insights from the body of NASA ATM-X research with the broader community.

The NASA ATM-X Insight Assessment project (Figure 1) included four major phases:

- **Phase 1 – Insight Assessment 1 (IA1):** The first phase focused on the development of the IA1 report, which synthesizes findings from 2018 NASA ATM-X literature and interviews with NASA experts.
- **Phase 2 – Insight Assessment 2 (1A2):** The second phase consisted of the IA2 report, which incorporates refinements from IA1 and focuses on NASA ATM-X research conducted in 2019.
- **Phase 3 – Insight Review (IR):** The third phase consisted of three virtual seminars on ATM and ConOps and Mission Planning, Weather and Noise Impacts, and Human Factors and Safety and Emergency Protocol. The goal of the seminars was to share research to date with the broader community, solicit feedback from the community, and engage in discussion about future research needs to help shape ATM-X.
- **Phase 4 – Final Insight Assessment Report:** Phase 3 led to the generation of this final report, which summarizes all findings from the IA1 and IA2 reports and includes community feedback from IR virtual seminars.

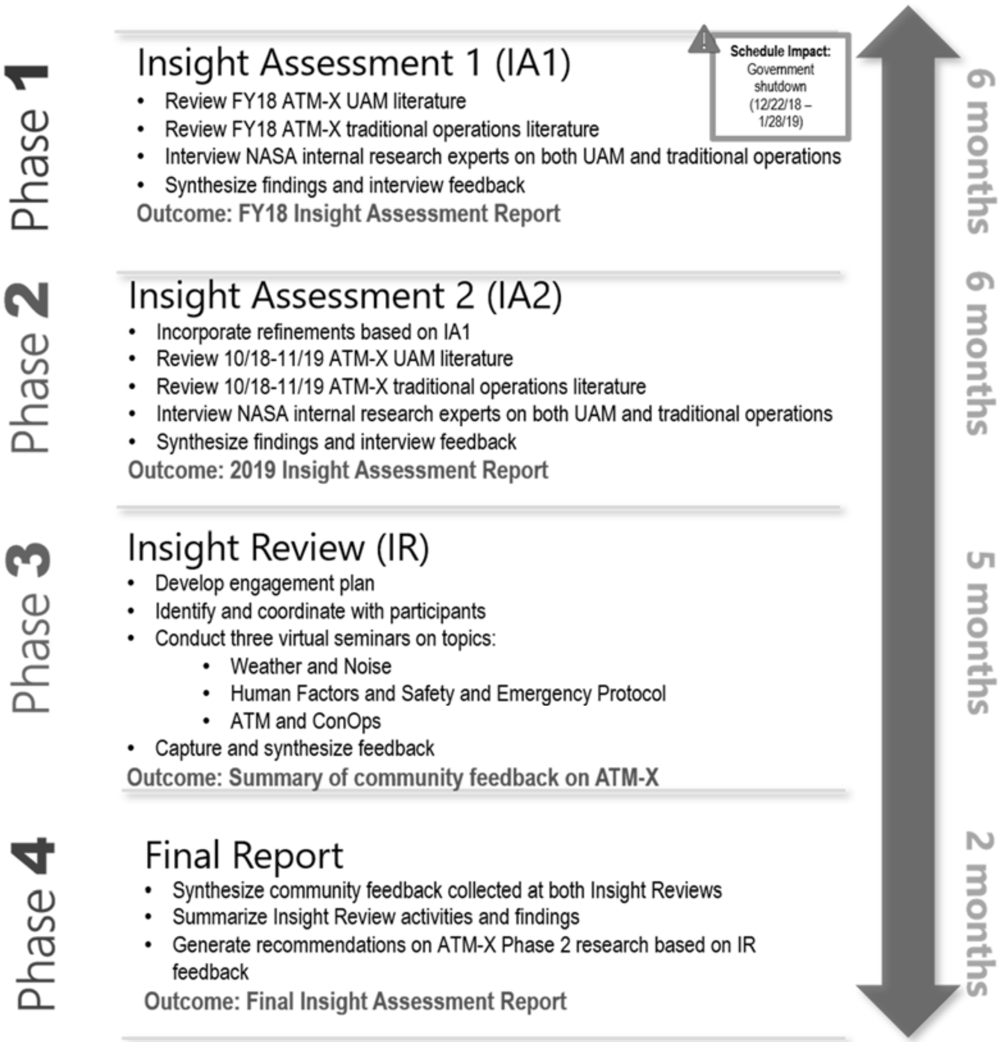

Figure 1. Overview of the NASA ATM-X IA Project

4 Approach

The research approach for the IA project included a detailed literature review of ATM-X publications pertaining to UAM and traditional operations, as well as interviews with NASA researchers. The team conducted one-on-one interviews with the NASA researchers in Phase 1 and extended the interviews to small groups for Phase 2. These interview methods were very effective for soliciting discussion and feedback. The team conducted interviews with individuals across multiple NASA ATM-X sub-projects with a special focus on cross-cutting Human Systems Integration. The sub-projects included Increasing Diverse Operations (IDO), Integrated Demand Management, and UAM. The interviews were used to supplement the literature review and reveal findings and details that were not explicitly described in the research papers.

4.1 Literature Review

The literature review process involved multiple reviews with increasing levels of detail, including:

1. A categorical review that entailed high-level sorting and categorization of the publications by several key characteristics such as focus area (e.g., UAM) and sub-category (e.g., flow management).
2. An initial, detailed review that focused on extracting relevant details from the document, such as key findings, lessons learned, and assumptions.
3. A comprehensive review by our SMEs to augment the initial review. SMEs were aligned to documents based on their expertise with the identified sub-categories.

We developed a literature review tracker to provide a centralized repository of key information from the literature (Table 1 below). This tracker enabled the systematic collection and direct comparison of relevant components from the research papers and was populated across all three levels of review described above.

Table 1. Key Literature Review Tracker Fields

Field	Description
Title	Title of the paper
Category	Traditional Operations or UAM
Sub-Category	More descriptive category under traditional operations or UAM
Key Assumptions and Constants	Research assumptions and constants controlled throughout research
Data Sources	Data sources referenced and used throughout the paper
Models Used	Any models used to conduct research
SME Reviewer	Booz Allen team member that will provide expert review
Relevant Keywords	Keywords that help describe the document
Key Findings	Major research findings as presented

Field	Description
Gaps Identified	Gaps in research findings, data, research process, and any obstacles/shortfalls
Lessons Learned	Improvements that can be made to the research process

The literature review conducted during Phase 1 included 15 publications (Table 2 below) covering both UAM and traditional operations focus areas from Fiscal Year (FY) 2018, which NASA provided for review. Additionally, the team performed a survey of publications published in 2018, external to NASA, that pertained to UAM, traditional operations, and ATM-X.

Of the 15 papers reviewed, seven pertained to traditional operations and the remaining eight focused on UAM. The traditional operations papers described concepts including flow management, system resilience and degradation, CTOP, and Trajectory Options Set (TOS) using techniques including Human-In-the-Loop (HITL) and real-time and faster than real-time simulations. UAM literature focused on the feasibility of UAM using contemporary NAS procedures and technology, infrastructure requirements, collision avoidance systems, automation, and separation and traffic management.

Table 2. List of Phase 1 Publications - Literature Review Papers and Authors

Title	Author(s)	Category	Year Published
Evaluation of Multiple Flow Constrained Area Capacity Setting Methods for Collaborative Trajectory Options Program	Gita Hodell, Hyo-Sang Yoo, Connie Brasil, Nathan Buckley, Conrad V. Gabriel, Scott Kalush, Paul U. Lee, Nancy M. Smith	Traditional Operations	2018
Impact of Different Trajectory Option Set Participation Levels within an Air Traffic Management Collaborative Trajectory Option Program	Hyo-Sang Yoo, Gita Hodell, Paul Lee	Traditional Operations	2018
Designing Graceful Degradation into Complex Systems: The Interaction Between Causes of Degradation and the Association with Degradation Prevention and Recovery	Tamyrn Edwards, Paul Lee	Traditional Operations	2018
Exploratory Analysis of the Airspace Throughput and Sensitivities of an Urban Air Mobility System	Kenneth Goodrich, Bryan Barmore	UAM	2018

Title	Author(s)	Category	Year Published
Simulation Evaluations of an Autonomous Urban Air Mobility Network Management and Separation Service	Christabelle S. Bosson, Todd A. Lauderdale	UAM	2018
TCAS Alerts from Simulated Urban Air Mobility Flights along FAA Helicopter Routes in Dallas-Fort Worth	Andrew Cone, David Thipphavong, Banavar Sridhar	UAM	2018
Using an Automated Air Traffic Simulation Capability for a Parametric Study in Traffic Flow Management	Heather Arneson, Anthony D. Evans, Deepak Kulkarni, Paul Lee, Jinhua Li, Mei Yueh Wei	Traditional Operations	2018
Silicon Valley as an Early Adopter for On-Demand Civil VTOL Operations	Kevin R. Antcliff, Mark D. Moore, Kenneth Goodrich	UAM	2018
Evaluation of Key Operational Constraints Affecting On-Demand Mobility for Aviation in the **Los Angeles Basin: Ground Infrastructure, Air Traffic Control and Noise**	Parker D. Vascik, R. John Hansman	UAM	2018
Constraint Identification in On-Demand Mobility for Aviation Through an Exploratory Case Study of Los Angeles	Parker D. Vascik, R. John Hansman	UAM	2018
A Throughput-Based Capacity Metric for Low-Altitude Airspace	Vishwanath Bulusu, Raja Sengupta, Eric R. Mueller, Min Xue	Traditional Operations	2018
Airborne Trajectory Management for Urban Air Mobility	Captain William B. Cotton, David J. Wing	UAM	2018
Development of a High-Fidelity Simulation Environment for Shadow-Mode Assessments of Air Traffic Concepts	John E. Robinson, Alan Lee, Chok Fung Lai	Traditional Operations	2018
Predicting the Operational Acceptance of Airborne Flight	Anthony D. Evan, Paul Lee, Banavar Sridhar	Traditional Operations	2018

Title	Author(s)	Category	Year Published
Reroute Requests using Data Mining			
ADS-B Mixed sUAS and NAS System Capacity Analysis and DAA Performance	Konstantin J. Matheou, Rafael D. Apaza, Alan N Downey, Robert J. Kerczewski	Traditional Operations (including UAS)	2018

For Phase 2, the literature review consisted of 10 additional publications (listed in Table 3 below). The four traditional operations papers described concepts including route automation, metrics, and flow management, while the six UAM papers focused on noise modeling, traffic separation/collision avoidance, scheduling, flow management, and human factors. Additionally, several authors whose papers were reviewed during Phase 1 also published papers for this phase. This provided the opportunity to assess the research progression and relevance to gaps identified in Phase 1. The team specifically saw this overlap in the papers relating to traffic flow management, human factors, rerouting, and traffic avoidance systems.

Table 3. List of Phase 2 Publications - Literature Review Papers and Authors

Title	Author(s)	Category	Year Published
Exploring Human Factors Issues for Urban Air Mobility Operations	Tamsyn Edwards, Savita Verma, Jillian Keeler	UAM	2019
Mission Planner Algorithm for Urban Air Mobility – Initial Performance Characterization	Nelson M. Guerreiro, Ricky W. Butler, Jeffrey M. Maddalon, George E. Hagen	UAM	2019
Exploration of Near-term Potential Routes and Procedures for Urban Air Mobility	Savita A. Verma, Jillian Keeler, Tamsyn Edward, Victoria Dulchinos	UAM	2019
Analysis of Interactions Between Urban Air Mobility (UAM) Operations and Conventional Traffic in Urban Areas: Traffic Alert and Collision Avoidance (TCAS) Study for UAM Operations	Vishwanath Bulusu, Banavar Sridhar, Andrew C. Cone, David Thipphavong	UAM	2019
Using Machine-Learning to Dynamically Generate Operationally Acceptable Strategic Reroute Options	Anthony D. Evans, Paul U. Lee	Traditional Operations	2019

Title	Author(s)	Category	Year Published
Accrued Delay Application in Trajectory-Based Operations	Husni Idris, Christopher Chin, Anthony D. Evans	Traditional Operations	2019
Simulating Fleet Noise for Notional UAM Vehicles and Operations in New York	Patricia Glaab, Frederick Wieland, Michel Santos, Rohit Sharma, Ralph Tamburro, Paul U. Lee	UAM	2019
Integrated Trajectory-Based Operations for Traffic Flow Management in an Increasingly Diverse Future Air Traffic Operations	Paul U. Lee, Husni Idris, Douglas Helton, Thomas Davis, Gary Lohr, Rosa Oseguera-Lohr	Traditional Operations	2019
A Scheduling Algorithm Compatible with a Distributed Management of Arrivals in the National Airspace System	Alexander V. Sadovsky, Robert D. Windhorst	UAM	2019
Prediction of Weather Impacts on Airport Arrival Meter Fix Capacity	Yao Wang	Traditional Operations	2019

4.2 Expert Interviews

While the literature review provided the core foundation for both IAs, targeted interviews with NASA experts provided valuable additional insight into the research that may not have been fully captured in the papers. These interviews were conducted with NASA experts, including many authors of the papers in the literature review, as well as other SMEs suggested by NASA.

For both Phases 1 and 2, the team contacted the NASA experts ahead of the interviews for an initial agreement to be interviewed. Upon agreement, the team sent a follow-up email invitation to arrange the logistics of the interview (e.g., date and time). For Phase 1, the team conducted one-on-one interviews (Table 4) focused on paper findings, given that most of the interviewees who authored the papers were included in the literature review. Unlike Phase 1, only three Phase 2 interviewees were authors of the papers reviewed. Therefore, the team prioritized small-group interviews focused on general discussion topics.

During interview planning, the team developed read-ahead materials based on our literature review to synthesize the interviewees' area of expertise, publications, and research interests. We then crafted and sent a set of initial interview questions to each interviewee as a read-ahead document a day prior to the interview.

Each one-hour interview included an interview leader, SME interviewer, and notetaker/recorder from the Booz Allen team, as well as the interviewee(s). Prior to the interview, we requested permission to record the discussion to ensure all components were accurately captured. All interviewees agreed to be recorded.

After each interview, the team transcribed and augmented the recording with notes taken during the interview. The team summarized the transcripts, and the SME reviewed the key findings. The following section presents the results of the interviews.

Table 4. List of Phase 1 Interviews and Topics

Interview Session	Sub-project	Date Interviewed	Topics Discussed
1	IDM	3/1/2019	Demand management, traffic flow management, flow constrained areas, automation, industry outreach, diversifying approaches, CTOP
2	UAM Coordination and Assessment Team	3/5/2019	Conflict detection, separation values, design constraint, proof of concept for UAM and future scenarios, future priorities for parameters, modeling
3	UAM and IDO	3/8/2019	HITL, FAA involvement, autonomous UAM and HITL factors, Tactical Separation Assured Flight Environment, Terminal Area Parallel Procedures Research
4	IDO	3/13/2019	Automation of traffic, ground operations and applicability to UAM, IDO, gate-to-gate scheduling, TBFM, CTOP
5	IDM and UAM	3/13/2019	Safe2Ditch, HITL factors, conflict detection, separations
6	UAM	3/14/2019	TCAS alerts for simulated UAM operations, vertipad infrastructure analyses, UAM separation minima analysis
7	NASA Aeronautics Research Institute	4/2/2019	UTM-inspired ATM, UTM ConOps as it applies to ATM and UAM
8	IDM	4/5/2019	ATM-X demand modelling, autonomous air traffic management simulations
9	UAM	4/8/2019	UAM separation minima simulation, NextGen air traffic control

Table 5 provides a list of Phase 2 interviews, NASA sub-projects, interview dates, and topics discussed. Although the papers guided the discussion topics, topics centered around more general, overarching concerns with UAM, traditional operations, and the future of ATM-X because fewer authors participated in the Phase 2 interviews.

Table 5. List of Phase 2 Interview Participants

Interview Session	Sub-project	Interview Date	Discussion Topic
1	HSI, ATM	11/15/2019	Human factors, routing, TCAS
2	IDM, UAM	11/15/2019	Mission planning, scheduling, weather, noise
3	UAM/UAS	11/25/2019	Routing, mission planning, TCAS
4	IDO, UAM	11/26/2019	Delay, Trajectory based operations (TBO), weather, routing
5	UAM	12/4/2019	Weather, noise, routing

4.3 IR Virtual Seminars

For Phase 3, the team was initially tasked with conducting an in-person IR workshop to discuss and review the findings from IA1 and IA2. This workshop was to be held in early April 2020 at a NASA facility and include the participation of 47 NAS stakeholders. This would provide an opportunity to spur more community involvement and gather feedback on the progress of the ATM-X IA project. However, due to the impact of COVID-19, the team had to alter this approach—instead conducting three 2-hour, virtual IR seminars. These seminars were broken up by topic area, which included ATM and ConOps and Mission Planning, Weather and Noise Impacts, and Human Factors and Safety and Emergency Protocol.

Before conducting the seminars, the team identified a list of 130 potential participants. This list included participants of varying backgrounds, as priority was placed on obtaining a diverse collection of perspectives in each discussion. Participant backgrounds included:

- Air traffic control
- UAS and fixed-wing operators
- Dispatcher
- Aircraft manufacturer
- Weather
- Regulatory
- Aviation human factors
- Aviation safety
- Airlines.

Table 6 provides a list of seminar attendee affiliation by session (names are not included out of respect for attendee privacy).

The team constructed virtual seminars using discussion topics, scenarios, and polls to elicit conversation. The team identified seminar topics using the findings from IA1 and IA2 as the foundation. Seminar participants were asked to select their seminar preference from the three topics: ATM and ConOps and Mission Development, Weather and Noise Impacts, and Human Factors and Safety and Emergency Protocol. The team used participants' selections to fill each seminar, making final adjustments to ensure balanced and diverse sessions and participation.

A NASA SME facilitated each 2-hour virtual seminar. The Booz Allen team used WebEx to host and record the seminar; recordings helped to assist with data capture. Each seminar introduced a number of discussion topics to guide conversation and assist with data collection for the final report. End-of-discussion polls gave participants the opportunity to directly provide answers to aid in prioritizing or understanding key findings and future research.

The team synthesized and reviewed the data collected from the polls, seminar notes, and recordings against the IA1 and IA2 findings to form the basis of the final report.

Table 6. IR Seminar Participant Affiliations

Virtual Seminar Group	Date	Affiliation	Number of Participants
Weather and Noise Impacts	5/1/2020	NASA (3 Facilitators)	5
		Intelligent Automation Inc.	3
		HMMH	2
		Quantitative Scientific Solutions	2
		Uber	2
		North Carolina Department of Transportation	1
		True Weather Solutions	1
		Booz Allen Hamilton	1
		Embry-Riddle Aeronautical University	1
		University Corporation for Atmospheric Research	1
Human Factors and Safety and Emergency Protocol	5/7/2020	Uber	3
		Intelligent Automation Inc.	2
		Windels Marx (1 Facilitator)	1
		NASA (1 Facilitator)	1
		FAA	1
		Government of North Dakota	1
		Florida Institute of Technology	1
ATM and ConOps and Mission Planning	5/13/2020	NASA (2 Facilitators)	5
		Boeing	4
		FAA	3
		Airlines for America	1
		Embry-Riddle Aeronautical University	1
		Embraer X	1
		MIT	1
		Port Authority of New York and New Jersey	1
		National Air Traffic Controllers Association	1

5 Results

This section summarizes the findings from Phases 1 to 3 and describes the results and outcomes of the final phase of this project. The team compiled findings using data extracted from the literature reviews and augmented by both the NASA expert interviews and NAS stakeholders during the IR seminars. The results are grouped based on sub-categories, focus areas, and any overlap in findings between these areas. This section also highlights lessons learned that researchers may find helpful during or after their research. These lessons will inform research best practices and improve the effectiveness and efficiency of future research projects by highlighting previous obstacles encountered.

Table 7 provides key findings from IA1 and IA2. The key takeaway from the Phase 1 literature review and expert interviews was that UAM and the associated increase in operations and demand can be potentially integrated into the NAS with contemporary operational methods and infrastructure. While vehicle capabilities, the scheduling of operations, and the role of the controller in managing UAM operations still need to be better understood, the current airspace can likely accommodate these new entrant operations in the near term.

Synthesis of papers and expert interviews from Phase 2 resulted in key findings around scheduling, delays, weather, and noise. Although the airspace currently has the capacity for initial UAM operations, uncertainty surrounding vehicle capabilities and ATM procedures with respect to WTO, dynamic routes, safety, human factors, and scheduling requires more research and tool development before a functional ConOps can be implemented. Current products can be leveraged to form the foundation for gate-to-gate scheduling, but further iterations and research will be necessary as operations scale and vehicle capabilities and demands become clearer. Public perception barriers, mostly due to noise, were also highlighted as a main focus area in Phase 2.

Table 7. Summary of IA1 and IA2 Findings

Category	Description
General	• There is a need to develop meaningful and objective metrics that can be used to measure the operational feasibility of integrating UAM in the NAS. Research reviewed on UAM integration was constrained to applying traditional operational metrics that are not well-suited to measure UAM and would likely benefit from an extension of these metrics or the development of new ones. • Regional variability in characteristics such as weather, airspace configuration, and infrastructure can have a significant influence on viability of UAM operations. This is an important aspect to consider when applying key findings and lessons learned from ATM-X studies with a specific location to other geographies. Additional research on regional variability would be beneficial. • When determining best practices for operation, the user value proposition must be considered due to the nature of short UAM flights. UAM, UTM, and traditional operation networks must be treated as one large transportation network where delay can be passed from one transportation mode to another. Weather mitigation, routing, and spacing strategies cannot severely impact total travel time, or users will opt out of UAM services.

Category	Description
ATM	• Current ATC and ATM procedures and airport infrastructure may be capable of accommodating the initial volume of VTOL UAM. However, specific route planning, scheduling, and UTM procedures will be needed to enable larger-scale operations. • For traditional operations, the consideration of accrued delay in place of existing metrics can reduce delay variance and increase capacity. As UAM operations start and begin to scale up, accrued delay will be important to maximize the efficiency of the NAS. UAM and traditional operations should be viewed as one network in which delay can transfer from one form of mobility to another. • Existing tools such as TBFM, TFMS, and Terminal Flight Data Manager (TFDM) can be leveraged to help schedule complex operations and alleviate workload. Researchers developed a framework for improving demand management by integrating select TBO capabilities with TFMS, TBFM, and TFDM tools. These solutions represent a solid foundation for future NAS integration of diverse operations and methods to further optimize operations within complex airspace with diverse air traffic. • To address routing, scheduling concerns, and ground operations, a strong ConOps must be defined that includes all potential risks, emergency contingencies, and communication strategies among vehicles, humans, and autonomous entities. • Current ATM-X traffic automation challenges include: o Exchanging data between TBFM and TFMS to create standardized schedules o Creating a strategy for sharing a hypothetical, consistent gate-to-gate schedule for all UAM and traditional flights with air traffic controllers, pilots, and dispatchers to direct their work o Resolving the large gap between tactical separation issues and strategic metering/routing issues. • With a network of vertiports, an overarching integrated scheduling similar to TBFM and TFMS can be used to manage vertiport arrivals, departures, and gate-to-gate operations if interacting with traditional ATC automation systems. • The use of TOS resulted in an overall reduction in delay and better utilization of capacity-constrained airspace and airport, indicated by high throughput rate. There was a benefit of TOS submission even when there was only a small number of participations. • Air traffic controllers are often able to use their own re-routing strategies and knowledge to alleviate traffic in different ways (rather than use CTOP) and achieve the same results, so this program should not be viewed as the only option. However, CTOP can incorporate flight operator preference through TOS allocation algorithms using user-indicated preference during the decision-making process.

Category	Description
Human Factors	• Medium and high-density UAM operations, under current rules and ATC engagement, are associated with high workload. In the short term, impact on ATC workload may be minimal through letters of agreement and reduced verbal communications by controllers. However, due to the sheer volume of traffic, workload will still likely remain high and further investigation into methods of reducing this workload are needed.
Noise Impacts	• Noise remains a critical factor in public opinion and acceptance of future operations, particularly UAM. However, research needs to be done to better quantify the potential noise impacts of UAM vehicles and explore potential mitigation strategies. • Day-night average sound level (DNL), the standard sound metric used by aviation stakeholders, does not accurately represent electric vertical takeoff and landing (eVTOL) vehicles. To better address noise impacts, DNL must be replaced with a contemporary metric designed to assess UAM operations.
Safety and Emergency Protocol	• New entrants may utilize existing UTM strategies, such as following roads, rivers, rail tracks, etc., to avoid densely populated areas in case of a failure. Current industry users are also building emergency protocols into their pre-flight planning, ensuring a solution to an emergency is built into each flight.
Weather Impacts	• Weather has the potential to impact UAM operations more intricately and profoundly than currently understood. Some of these impacts may be similar to those influencing other modes of aviation such as helicopters and general aviation, but additional research is needed on weather disruptions specific to UAM vehicles and operations.

The Phase 3 IR seminars captured feedback and inputs from key NAS stakeholders on findings and gaps from Phases 1 and 2. Discussions during the IR built off, expanded upon, and prioritized findings and gaps identified in the previous two phases. Final findings, which are included throughout the results section below, are synthesized from all three phases of the ATM-X project and reprioritized to assist future ATM-X research.

5.1 Key Findings

This section features key findings from the summation of all three phases of this project identified through literature reviews, expert interviews, and the IR seminars. Findings represent interdisciplinary, high-priority knowledge on the current and future state of the NAS, traditional operations, and AAM. Where applicable, Phase 3 findings are referenced or tied back to IA1 and IA2 findings and gaps.

This section groups findings into five critical focus areas that emerged during the reviews and interviews. The nature and themes of the findings across all phases of the project drove the grouping of these focus areas, each of which are briefly described below:

- **ATM**: These findings relate to ATC, routing, separation, traffic deconfliction, trajectory, scheduling, and communications infrastructure of traditional and autonomous or remotely piloted operations.

- **Human factors**: These are findings that consider, among other things, the human impact or reaction on automation, communication, proposed ATM methods, or increased workload.
- **Noise impacts**: These findings relate to any UAM or traditional operation noise-related impacts, technology, or policy.
- **Safety and emergency protocol**: These findings relate to any methods, technology, or policies guiding the handling of emergency situations or general safety of UAM or traditional operations.
- **Weather**: These are findings that pertain to the impact of weather on ATM, vehicle capabilities, or pilots, plus any weather data or sensors.

5.1.1 ATM

With increasingly diverse operations proposed for the NAS, experts have explored and studied systems and solutions for managing the scheduling, routing, and separation of diverse air traffic. These diverse operations pose challenges for controllers and operators due to performance and mission differences between aircraft. Well-defined and understood separation standards; roles and responsibilities; and communication links among controllers, pilots, and autonomous aircraft will be crucial for integrating traditional operations with scaled UAM.

Traffic Separation – The current ATM paradigm is capable of handling the initial volume of UAM aircraft, but fully scalable operations will require current business practices, procedures, technology, and training to evolve. As operations scale, and strain increases on controller workload, there is concern that the current paradigm will not be able to meet current required safety levels to manage the increased number of vehicles. NAS stakeholders from the IR emphasized separation standards and procedures as the fundamental priority for enabling scaled integrated operations near large airports and urban centers. If manned aircraft are expected to maintain separation from unmanned aircraft, remote ID and cooperative and non-cooperative surveillance will be critical. Controllers will also need a well-defined mechanism to initiate separation standards and procedures when they become available.

Communication Infrastructure – As autonomous vehicles enter the airspace, strong communication links between aircraft and controllers will be necessary to enable scaled operations. A broad spectrum of autonomous aircraft will vie for the same low-altitude, urban airspace. Despite varying capabilities in automation and communication abilities, effective communication between vehicles and the airspace management system will be necessary to maintain a safe environment. Controllers and NAS users will not care about the level of autonomy as long as instructions are followed. Because it will be easy for autonomous vehicles to operate if ATC bears the responsibility of routing and separation, the challenge lies at the human interface from the controller standpoint. Whether via voice link or data link, IR participants contended that the most important aspect of communication is speed. The successful integration of autonomous and remotely piloted operations will rely on creation of a fast and robust communication architecture.

Roles and Responsibilities – For any new ATM paradigm, all parties must understand their roles and responsibilities to function. New standards, procedures, and tools will be meaningless if agents do not understand and adjust to their new responsibilities. Standards must be clear to understand who has the responsibility of separation, how to communicate with and direct unmanned vehicles, and how to respond when communication structures break down.

Government and third-party service providers may also need to take on new roles and responsibilities. One centralized Air Navigation Service Provider will be necessary for an integrated airspace, improving the ability to enable existing service providers to continue services. ATM must delineate roles and responsibilities between service providers in a manner that is both cost effective and scalable.

Scheduling and Delay – As observed in IA1, researchers began using TBFM and TFMS to create standardized schedules to reduce scheduling workload and complexity (Yoo, et al., 2018). IA2 also showed that existing tools can be leveraged to help schedule these complex operations and alleviate controller workload. Researchers developed a framework for improving demand management by integrating select TBO capabilities with TFMS, TBFM, and TFDM tools (Lee, et al., 2019). This combination was applied to support surface, departure, and arrival metering and dynamic reroutes for weather. Airport throughput prediction models were also incorporated and provided an aid to improving current traffic flow management. These models benefit operators by improving their understanding of uncertainty associated with weather-impacted airport meter fix capacity and provide a tool to learn from past experiences in similar scenarios. The solutions represent a solid foundation for future NAS integration of diverse operations and methods to further optimize operations within complex airspace with diverse air traffic.

Diversified operations will also impact delay. One Phase 2 paper (Idris, Chin, & Evans, 2019) demonstrated that using accrued delay as a metric could help integrate decision-making across multiple sectors, leading to more efficient and equal access to the NAS. For both traditional and UAM operations, prioritizing flights that have already accrued high delay due to a constrained runway will significantly reduce overall delay and its variance. Reducing the delay variance will yield higher flight capacity by decreasing flight block times, which are often inflated by airlines to accommodate potential delays.

Routing – Mission planning for a new integrated airspace will require a strong ConOps to ensure separation and safety and reduce delays. The IR and interviews with NASA SMEs revealed that integration will be a challenge, especially regarding limited route options, given the relatively short duration of flights. However, potential solutions are currently available for use, along with solutions in development for future operations. Current helicopter routes can be used but will have to be reevaluated as operations increase and traffic density along these routes grows. Terminal Area Route Generation Evaluation, and Traffic Simulation, a route planning tool developed for the Federal Aviation Administration (FAA), allows a user to create simulated NAS-compliant, flyable routes for several different aircraft types. This tool can help with the development of speculative routes to alleviate traffic density in UAM intensive airspace.

Traffic conflicts will naturally become more common as operations density increases. However, methods such as a Mission Planner algorithm for UAM operations can be used to help plan conflict-free trajectories for UAM aircraft. This builds on a similar methodology mentioned in IA1 regarding the use of AutoResolver for deconfliction (Bosson & Lauderdale, 2018). However, in IA2, the Mission Planner’s algorithm strategy was to place constraints on the mission trajectories and vertiports to provide conflict resolutions. Under the research test conditions, most strategies show good performance. When using vertiport constraints, all strategies showed good performance. Tools like Mission Planner may be useful to characterize and actively alleviate conflict generated by UAM operations. Other options also exist that leverage current aircraft routing and scheduling.

Low-altitude new entrants can also use dynamic routing (routes that change based on the situation and constraints) to ensure separation and traffic deconfliction. Airport configuration will be important to enabling dynamic routing. Depending on the airport and its configuration, early UAM integration may not be difficult. At high capacity, routes must be procedurally deconflicted so fully dynamic routing is unrealistic. More space will likely be available if decisions are made based on airport configuration. Changing configurations, however, is work intensive, and participants must understand roles and responsibilities for dynamic routes to not interfere with major corridors.

Regional authorities have already experimented with dynamic corridors and found that, in the short term, they can be managed in a similar manner to helicopters. In the longer term, there is concern that the communication paradigm will not be able to meet safety standards for increased operations. A mix of static and dynamic corridors will not be feasible until separation standards that allow for close proximity can be implemented.

Operational disruptions will be a driver of the future ConOps. The system needs to be flexible enough to handle operations changing or vehicles turning around midflight. The future ConOps for high-density UAM and AAM operations will likely be tightly metered and utilize time-based metering. Therefore, corridors must be bi-directional to mitigate constraints or other unforeseen operational impacts. For autonomous and remotely piloted operations, there may be instances when an aircraft loses a command control link (lost link), and ATC cannot direct the aircraft. Clear procedures, roles, and responsibilities will be needed for the degradation of links. Having an ATC that can deal with a non-responsive system is crucial.

5.1.2 Human Factors

Research synthesis and input from NAS stakeholders underscored the challenges of higher demand and workload for air traffic controllers created by future high-scale UAM traffic density. IR participants in the seminar discussed the potential to segregate the airspace to provide a distributed workload for controllers. However, in terms of cognitive performance, it seems more difficult to gain situational awareness when “jumping into” a problem, rather than continuously monitoring the surroundings. For example, workload would more manageable for controllers if specific airways were reserved for unmanned vehicles and/or dedicated to automated systems. However, as future autonomous operations reach higher scale, a fully segregated airspace will likely no longer be feasible. If the density of unmanned flights increases, but controllers continue to control manned aircraft only, then their workload will not change. However, more unmanned flights could mean fewer manned aircraft—hence, fewer flights to control.

A case study (Edwards, Verma, & Keeler, 2019) looked at an HITL simulation focused on identifying the effect of UAM traffic density, airspace routes, and communication procedures on subjective workload and efficiency-related task performance. The study observed optimized routes to reduce the verbal communication workload, decreased workload, and increased performance efficiency. This signified that, in the short-term implementation of UAM, workload could be minimally impacted through letters of agreement and reduced verbal communications by controllers. Alternatively, hiring more controllers would increase the number on rotation and may mitigate performance degradation from fatigue due to increased workload. While unmanned and automated systems increase in popularity, there will likely be fewer manned aircraft for air traffic controllers to manage.

Another paper (Edwards, Verma, & Keeler, 2019) indicated that, while small-scale implementation of UAM operations can be managed with human ATC, contemporary automated UTM methods must be utilized once operations scale up. At this point of the development of UAM, automation of final phases of flight represents a safety risk as the industry is not technologically ready to automate the final phase. The difficulty of the urban environment will bring new factors to consider, in addition to well-known hazards such as potential fog, animals, foreign object debris, or humans on the airfield. Automation will likely start with small accomplishments and progress through increasingly complex tasks to achieve full automation. Overall reliability should be considered when designing systems to achieve full automation. As with manned systems, UAM must always have automation redundancies to improve reliability. These redundancies and back-up systems, such as pilots in the cockpit or remote pilots on the ground, can help autonomous vehicles achieve high system reliability.

5.1.3 Noise Impacts

Due to public perception, health, and environmental concerns, researchers aim to reduce noise generated by UAM operations in a variety of ways, including applying traditional flight operation approaches. Some of the literature (Glaab, et al., 2019) and expert interviews highlighted potential noise mitigation strategies. One strategy is to distribute operations both spatially and temporally to avoid overloading communities with excessive noise. Demand at a given time will influence or determine temporal dispersion. Spatially, noise disruptions are highest during takeoff and landing phases, and noise reduction will require more nuanced understanding of ATM ConOps for integrated operations. IR seminar participants noted that aircraft design is the root cause of noise related to operations and that any research into minimizing the noise output from these vehicles should be prioritized. NASA is researching strategies to minimize noise associated with aircraft design, such as phase rotors, noise canceling, and shielding.

In addition, industry participants during the IR indicated preference for a consistent strategy for noise and demand mitigation/handling across all markets, rather than fine-tuned local recipes. Some local considerations are necessary, but a consistent strategy is preferred. However, this may not be feasible as technology advances and ambient noise of cityscapes change. Moving forward, it will be important to factor local ambient noise into any strategy.

Additionally, one SME pointed out that noise is currently used as a catchall issue to constrain helicopter operations, which could similarly impact UAM operations. A New York City helicopter crash in the 1970s raised safety concerns and changed public perception around urban routes. Had the accident not occurred, urban helicopter operations today could look very different. As an easily identifiable nuisance, helicopter rotor noise may act as a proxy for other issues such as safety. Therefore, it is important to consider all public perception concerns when managing noise impacts.

5.1.4 Safety and Emergency Protocol

Safety has always been paramount in the aviation industry. New entrants adding to higher traffic density will only act to increase the probability of emergency situations. Understanding and mitigating these situations will ensure safe integration of emerging technology and ATM methods into the NAS. Expert interviews described proactive mitigation approaches that mimic traditional operations approaches, such as incorporating “backup” or emergency runways/vertiports into the scheduling so that an emergency landing area would always be available. Existing UTM operations often follow roads, rivers, rail tracks, etc. to avoid densely populated areas in case of a failure. Current industry users, such as Uber, are also building emergency protocols into their pre-flight planning, ensuring that a solution to an emergency is built into each flight.

The fuel reserve requirements for manned operations are based on minutes of time available, not on distance. Commercial aircraft are currently required to have at least 30 to 45 minutes of reserve fuel depending on the type of engine. Similar regulatory requirements are needed for battery-operated vehicles. The industry must decide between assigning minutes of time or distance to reach the alternate. NASA is researching improvements to batteries and entire electric propulsion systems to determine minimal performance standards for batteries on these aircraft.

Pre-flight procedures must be adjusted to become more efficient and automated to accommodate a future high frequency of flights with no human involvement. At the time of this writing, UberCopter has been operational for almost a year in New York City, and the company has gathered useful findings from the experiment.

Current passenger-processing protocols in traditional airports may not apply to the automated environment of a vertiport and will require faster and more efficient protocols. Pre-flight activities, such as weight and balance, passenger manifest, as well as a passenger safety briefing, need to be completed within minutes. Ultimately, the goal is to minimize the turnaround time while ensuring safety. The industry will need to go above the current regulations requirements for traditional operations. Safety requirements exist for operations under Part 121 but not for Part 135 charter operations, which is the category in which UberElevate would expect its operations to belong. The same safety processes for commercial airlines need to be scaled and customized to this unique operational model.

The industry will also need to consider the general public's perspective on safety. The public's perspective changes quickly based on the global environment. In the 1960s and 1970s, there were many more aircraft accidents than today. The industry responded by improving the technology and safety, which caused people's perception to change for the better. Safety is largely responsible for people's willingness to use any vehicle, even more so for air transportation. The automated nature of these flights and lack of pilots onboard will reinforce passengers' and non-users' perception of safety. External factors, such as passenger screening, need to be anticipated so the industry learns from traditional operations and crafts new preflight protocols to provide a proactive, instead of reactive, security stance. UberElevate is investigating various initiatives similar to those applied in today's airports but on an innovative scale. Such procedures could include a physical screening structure, through which each passenger would pass, similar to airports today; an evaluation against the no-fly list; etc.

5.1.5 Weather

In all phases of the project, NASA SMEs emphasized that weather continues to be a challenging and understudied area of future operations of UAM in the NAS. The SMEs indicated that weather will impact UAM more than traditional aviation due to, for example, aircraft design thresholds, operations density, and flight duration. IR participants also noted that weather will impact the ride comfort and quality for passengers and could reduce willingness to fly.

Microclimates in cities and low-altitude flying near buildings, people, and property make WTO for UAM flights riskier and more difficult to control. eVTOL aircraft will not hover as effectively as helicopters and may not be stable on every axis, thus making them more susceptible to the impacts of winds. Additionally, lower power reserves will impact abilities to hover or endure strong winds as successfully as helicopters.

Weather will also significantly impact UAM vertiports, which NASA SMEs indicated will likely be more traffic-rich than traditional airports. Similar to current operations, wind direction will be a primary factor in vertiport configurations, which could result in forcing vehicles to fly over people or gates during the riskiest phase of flight—vertical landing. Real-time, high-resolution weather observations, analysis, and forecasting will be critical to user decision making and enabling WTO. During the IR seminars, participants identified starting with the known weather impacts to traditional operations for determining impactful weather to UAM operations. Typical aviation observations and forecasts do not have sufficient temporal or spatial resolution to support the precision needed by UAM operators for these short-duration operations. One potential solution to improve weather observations and by proxy, forecasts, is to mount weather sensors on UAM vehicles and enable real-time data sharing between operators, other vehicles, and the weather enterprise. The additional data from these sensors will also provide data to help feed into models and improve forecasts.

5.2 Gaps and Shortfalls

In all three project phases, the team identified critical gaps and shortfalls that would greatly benefit understanding of ATM-X and should be prioritized in future research.

Phase 1 identified a need for additional research pertaining to controller workload, an important factor in determining functional allocation of requirements to systems, humans, or vehicles to meet expected demand and handling. Further research is also needed to understand how best to integrate future systems and automation into the controller environment to ensure consistent, effective, and efficient integrated autonomous operations. Similarly, research showed the need to prioritize filling information gaps during system degradation. Phase 1 also highlighted the need for future studies to emphasize the psychology of human interaction as well as team and personality dynamics during system degradation.

There is also a need to develop meaningful and objective metrics that can be used to measure the operational feasibility of integrating UAM in the NAS. Researchers struggled without a consistent and well-understood suite of tools and associated metrics that could be used to measure the feasibility and success of new-entrant technology deployment into the NAS and for ATM-X.

ATM tools and their potential applicability to support UAM integration into NAS surface movement and airborne requirements need more research as well. This includes tools such as TBFM, TFMS, CTOP applicability to UAM, arrival and departure planning tools, surface movement surveillance such as ASDE-X, multilateration systems, and airport systems such as ramp control towers.

Phase 2 addressed some of the gaps identified in Phase 1, while reinforcing the need to address others. Some of the major areas addressed included the need for human factors and controller workload research as well as ATM procedures and their applicability to UAM. Metric identification remains a challenge as stakeholders are slow to depart from familiar metrics used in traditional operations. Regional diversity remains a gap in current research, as most research focuses on only a few metropolitan areas. Regional factors have substantial influence on the performance of ATM-X for a given location; therefore, more studies are needed to address regional diversity.

More importantly, research from Phase 2 also uncovered a variety of new gaps and shortfalls in UAM knowledge. Due to the uncertainty surrounding a heterogeneous suite of the vehicles and networks requiring collective action, the integration of UAM into the NAS faces a host of questions.

Table 8 describes the gaps identified in Phases 1 and 2.

Phase 3 presented the gaps from Phases 1 and 2 to a diverse group of NAS stakeholders for their review and prioritization. IR seminars reinforced high-priority gaps identified in IA2 and expanded on the specific areas relevant to the varied disciplines of IR participants.

Table 8. Summary of IA1 and IA2 Gaps

Category	Description
General	• Regional specificity in research makes extrapolating findings difficult. • There is a lack of common metrics that determine the feasibility and success of UAM adaption and adoption into existing ATM and NAS procedures and operations. • Gaps exist in understanding interactions between UAM, unmanned, and traditional aircraft operations. • Current gaps and shortfalls to automating traffic management such as data exchange between current scheduling products; sharing any integrated scheduling with controllers, pilots, and dispatchers; and filling the gap between tactical separation issues and strategic metering and routing issues.
ATM	• Short urban flights create challenges to designing flexible routes to avoid aircraft, weather, delay, and ground infrastructure, while keeping the value proposition up for consumers. • Delays can be reduced through even minimal TOS participation, which could motivate early adopters. Further research and coordination with airlines to understand their perspective on TOS participation would be beneficial to assess systems and human factors components in their decision-making as part of CTOP. • Uncertainty in the system must be accounted for to reduce delay. Understanding uncertainty and procedures for handling non-normal situations will be crucial to the next stage of scheduling. • Significant gaps exist in the management of arrivals and departures at the final approach and takeoff area at future high-demand, high-density vertiports. • Further research is required to discern the applicability of UTM to UAM. • Current departure and arrival systems do not exchange information readily and produce two different products for end-users. The data exchange between systems remains a gap. • Research is needed on the interaction between tactical separation and strategic scheduling for all phases of flight.
Human Factors	• Gaps remain in delineating human roles, responsibilities, and level of involvement in UAM system management.
Noise	• Noise remains elusive to quantify for UAM. New metrics will likely need to be created. • Different vehicle configurations could have vastly different noise characteristics, even when vehicles look alike.

Category	Description
	• While sound and noise mitigation currently exists in traditional operations through traffic flow management, utilizing such practices in UAM must be further explored. • The true impact of noise on public perception needs more research. • Procedures that focus on minimizing sound disturbance to communities are not yet considered or fully understood.
Safety and Emergency Protocol	• In emergency situations, it is unclear how to ground the entire fleet. • Roles and responsibilities between automated systems and human controllers and pilots during emergency situations must be addressed. • Identifying and standardizing the proper sensors on vehicles to make emergency landings is also critical. Automated landing functions must determine if the emergency area is clear during the emergency event. • Contingency operations for emergencies in urban and high-demand areas need to be explored.
Weather	• Weather impacts on ground operations at vertiports remains a gap. Wind direction may affect the vertiport configuration, forcing vehicles to fly over people or gates during the vertical stage of landing, the riskiest phase for eVTOL vehicles. • Some cities see frequent weather that is potentially impactful to UAM operations and will impact operations. • Mission planners and scheduling bodies must learn the proper methods to account for weather. Without granular weather observations and forecasts, UAM operations and routes lose flexibility, hindering the scope and scale of flights.

The gaps and shortfalls in this section follow the focus areas outlined in Key Findings.

5.2.1 Air Traffic Management

The proper approach to integrating and separating the airspace for new entrants requires research and planning. Even more than separation standards, explicit procedures with clearly delineated roles and responsibilities across the UAM industry are necessary for future manned and automated operations. Decisions must be made for how to address these gaps and mitigate inherent uncertainty in the system. A strong ConOps will be necessary to delineate procedures, roles, and responsibilities.

Communication – Air traffic control and management issues are frequently communications issues. Communications procedures require ATC to quickly determine if it is more effective to relay information through datacom links or via phone. A mixed communications system with both data and voice links will add to an already impacted workload. Basic data links are in use today, but there is great opportunity to expand their use and to work in synch with voice links. The process should initially focus on strategic communications over tactical communications. Finding the right balance will be necessary for controllers to effectively communicate to all aircraft and ensure separation of the airspace.

As scale increases, industry will likely look toward connected aircraft with advanced information sharing (e.g., intent information, position information, directives). Ultimately, as more aircraft enter the airspace, the system may start seeing chokepoints in communications frequencies based on the utilized and available frequency spectrum in certain areas. Spectrum management, and new ways to use the frequency spectrum, are key research priorities for scaled communications.

Services, Roles, and Responsibilities – An important element in defining roles and responsibilities will be service delegation. It is likely easier to enable existing government and third-party providers to continue to provide services. However, third-party service contracts are costly, and scaled user costs may become unjustifiable to the general public. Finding a way to keep services scaled and cost effective will be critical to widespread adoption of UAM. Exploring different levels of service to different aircraft may keep costs accessible to the general public. Additionally, enabling more competition and allowing industry competition and the market to drive costs down may help to enable scaling.

Liability plays a large role when considering separation standards and procedures to accommodate autonomous and remotely piloted operations. The radar-based controller separation was created to shift liability from individual carriers to government. If self-separation is implemented, then the liability shifts back the carrier. A key impediment to self-separation that must be addressed is liability inertia.

Delay – NASA SMEs admitted that many types of delay are unavoidable. Therefore, the UAM, UTM, and traditional aviation networks must be treated as one large transportation network where delay can be passed from one transportation mode to another. In the case of UAM, delay should be equitable, but not necessarily equal. Given the short flight times of UAM operations, the high density of operations at vertiports, and the limited hovering ability of eVTOL vehicles, UAM must avoid long delays as much as possible by avoiding multiple impacts and improving pre-departure planning.

Routing – Integration of UAM into the future ATM system will be a challenge and, given the relatively short duration of flights, routing options can be limited. As services and scale increase and factors such as noise and weather are considered, the short nature of UAM routes adds additional routing challenges. Unlike with traditional passenger flights, less direct routing or changes in trajectory can severely impact the value proposition for customers. A well-defined ConOps is needed to assess routing options so that reroutes do not affect the mobility and time-saving benefits of UAM. If ATC is to handle dynamic UAM routing, additional tools are needed to meet mixed equipment and varying traffic flows.

System Uncertainty – Much uncertainty remains in UAM operations. Parking, flight time, and weather, for example, inject uncertainty into a system with a limited ability to absorb delay. Dispatchers will not have time to generate new flight trajectories, so most mitigation must be done prior to departure. In this case, SMEs advocated for creation of a strong ConOps to determine the best strategies for mitigating delay and scheduling flights. Understanding the impacts to vertiport operations is still a gap, and with such short operations, there is limited ability to buy back and make up any delay. The human decision-making component of ATC introduces unrecoverable delay into the system, unlike in traditional operations. The manually intensive processes that controllers go through (up to 10 minutes) to deconflict traffic further contribute to delays to UAM flights.

Understanding how much uncertainty the system can maintain before breaking is crucial to the next stage of scheduling. The question of scheduling must include all stakeholders of the NAS when looking at operations flying into a Class B metered airport. Instead, the flight crew coordinates with three or four parties throughout their flight to generate re-routes. However, improper coordination or mishandled communication can compound delay as it increases workload for all involved.

Some operators may plan to have one person operate multiple autonomous/remotely-piloted vehicles. This scenario presents a challenge for vehicles to respond to instructions quickly. It also introduces the potential for a single point failure that could have large safety implications if roles and responsibilities rely on air traffic to communicate with a remote pilot in command of multiple vehicles. If that communication link is lost, they may lose visibility to many aircraft flying simultaneously. As autonomy increases, the issue becomes how vehicles can deal with these lost-link situations. In the long term, agents must be smart enough to deal with these situations on their own, but gaps remain in methods of surveillance and diagnosis.

ConOps – Mission planning will rely on a ConOps, which still needs continued research efforts to create. The vehicle's propulsion systems, number of rotors, and configuration (fixed vs. tilt) will have different performance envelopes, cruise speeds, and approach and departure profiles. These vehicles will operate very differently from today's commercial operations, and routes will have to be adjusted to meet varied vehicle capabilities. Vehicle suppliers do not have any ConOps for ground operations, and heterogeneity in vehicle design and configuration will determine the types of missions that they can undertake. Spacing challenges will have to be solved on the ground, and ground operations have implications that back into scheduling plans, limiting scalability. Introducing electric powertrains will also create new challenges due to power and capacity constraints. Most problems can occur in the vertical stage, and lower reserves will demand a tighter relationship between the vehicle, NAS, and autonomy projecting problems.

The SMEs interviewed were weary of applying playbook routes to UAM operations. Unlike with playbooks in traditional operations, UAM requires dynamism, integration, and flexibility. Ensuring all the automated tools interact properly and coordinate all the heterogeneous systems to have collective behavior is a major challenge. Preflight analysis will not be enough, as vehicles must constantly communicate and exchange information with each other and with regulatory bodies like the FAA. A well-defined ConOps that requires more research and detail to design will be crucial.

When interacting with other types of traffic (e.g., commercial operations), a UTM-like approach may be necessary and situational awareness must be reinforced. With a high density of traffic, onboard detection systems will be critical. Vehicle control will be easier, but interaction with other vehicles in the airspace will be much more complex. Decision makers must consider if certain types of vehicles will require access to certain air space, such as Amazon's UTM model, or if the bar should rise for everyone, which would require operators and/or pilots to invest in capital to upgrade avionics and communications equipment.

5.2.2 Human Factors

Many of the gaps identified were specific to traditional operations and relate to the role of human dynamics and system complexity in system degradation within the NAS. Recent human factors research (Edwards & Lee, 2018) has begun to characterize system degradation. However, further assessment is needed to fully specify interactions between system components including technology, environment, and humans that cause the most risk to the overall system, and in turn, how to predict and mitigate the effects. Any controlled airspace with Instrument Flight Rules traffic is required to have some type of interaction with controllers. Studying the workload in areas with significant Visual Flight Rules (VFR) air taxi service, like New York City, may be useful since any increase in workload will cause a system degradation. This could serve as a case study given the similarity between VFR helicopter air taxi service and UAM.

Recent research has also not yet focused on the potential impacts of personality dynamics and psychology on the system, as well as the effect that system degradation has on team dynamics and the functional capabilities of systems in recovering from such events. Resiliency is built into the NAS; however, resiliency options have not been fully studied in the areas of human performance. Another potential area of future research relates to characterizing the motivation for TOS participation by airlines. Several of the recent ATM-X studies revealed that delays can be reduced through even minimal TOS participation, which could motivate early adopters. Further research and coordination with airlines to understand their perspective on TOS participation would be beneficial to assess systems and human factors components in their decision-making as part of CTOP.

Although Phase 2 literature evaluated ATC's ability to manage UAM with human controllers (Edwards, Verma, & Keeler, 2019), gaps remain in delineating human roles, responsibilities, and level of involvement in UAM system management. With the high-density operations projected for UAM, automated UTM tools will likely be required. Interviewed SMEs expressed vast opportunity in designing this system, with a focus on the impact of reduced human operator involvement and increased automation. When assessing human involvement, emphasis must be placed on the safety and efficiency of UAM operations as well as the integration of UAM with traditional ATM.

In integrating UAM operations into the airspace around busy airports, one must consider the synergy between the controller and the pilot. Removing the pilot from the loop will decrease the amount of information available to controllers and increase their responsibility. The type of information gathered and shared by the pilot is immense. There are situations in which pilots leverage their extensive experience if an algorithm is not efficient. They also interact with other individuals on the radio to share pieces of information that may not be readily accessible to them. All pilots listen to the radio, and someone can jump in to provide situational awareness to another pilot that they may not see. Controllers may have been on station for hours and have a very precise picture of all the aircraft in their airspace, whereas an automated system may have just “logged into” the airspace and may lack critical information. Overall, workload will likely remain high due to the sheer volume of traffic that is expected within a few years of the beginning of UAM integration. More research, case studies, or tools to reduce workload developments need to be further investigated, developed, and implemented.

How unmanned aircraft are sequenced with current traffic will impact airport operations. Increased operations will intensify the difficulty in sequencing those flights in and out, in addition to continuing to handle commercial traffic. A new metering system will likely be necessary. It is still unknown whether both manned commercial traffic and unmanned vehicles will share the same runway. ATM-X is exploring how the airspace will need to be modified around airports and urban vertiports. The more changes there are, the longer they will take to deploy. Air taxi is currently the closest existing model to UAM. Research will need to examine how they interact with the current design and regulations and how UAM operators can redesign their operating model to support the growth of this new model.

Full automation will likely require multiple phases. Many cargo operations are unmanned but still interact with humans on the ground. Humans will always be in the loop to ensure multiple layers of separation assurance. It is still unclear which types of tools could work together to improve reliability. In the meantime, before full automation is achieved, there could be a second layer of controllers on the ground overseeing the unmanned aircraft.

5.2.3 Noise Impacts

Interviews with Phase 1 NASA SMEs indicated noise was one of the largest constraints to high-volume UAM operations. Phase 2 found that noise remains elusive to quantify for UAM operations. This is in part due to the diverse nature of vehicle technology as well as uncertainty in UAM operation and routing constraints. Finally, in Phase 3, IR participants identified the need to better understand the flight profiles that will be typical of UAM aircraft operations. Vehicle capabilities must be better understood before flight profiles can be used for noise mitigation or modeling purposes.

These uncertainties will need to be better understood to quantitatively evaluate the noise impacts of UAM. For example, choosing the proper sound metric for research is crucial. One study (Glaab, et al., 2019) utilized the DNL because it is the standard; however, it does not properly represent eVTOL vehicles. Metrics will have to be revised, but DNL is the metric that community planners and the Aviation Environmental Design Tool currently understands, and it is the metric used in regulatory proceedings. In addition, IR participants indicated that the flight profiles of the UAM vehicles are also key to helping determine the noise impacts and mitigation strategies for integrated operations.

While addressing noise is important, public perception may equally depend on other factors. Ensuring and marketing a safe system that does not cause harm to non-users and reinforcing the idea that UAM can be accessed by the average person may reduce the public’s projected fear of noise.

5.2.4 Safety and Emergency Protocol

Though the UAM community is aware of the necessity for rapid response emergency protocols, gaps remain in research and decision making to implement them. NASA is starting research into grounding all vehicles quickly in the event of a major emergency, but the process is still unclear.

Right of way will be one of the tools to help define emergency procedures. Aircraft carrying humans will need to have a higher priority than those carrying cargo or conducting aerial surveying. If an emergency (e.g., 9/11) requires the airspace to be shut down for any given amount of time, how will all automated systems decide amongst each other which aircraft will have the highest priority to land? Additionally, if there is a total shutdown and humans need to jump in, what would the transition between automated systems and humans look like? Would flight attendants be dedicated to assist passengers with exit procedures?

Communication may be the most important factor in synchronous emergency responses. Vehicles must communicate with each other to avoid attempted landings in the same area. UTM and FAA systems will need to communicate and share information. Various interactions between vehicles operating in close proximity and the point at which a human controller takes over must also be examined. It is also critical to identify and standardize the proper sensors on vehicles to make such landings. Automated landing functions must determine if the emergency area is clear during the emergency event (e.g., a soccer field that may have a game going on). Current reserve requirements will likely have to be much lower for eVTOL vehicles (e.g., Uber Elevate is planning a 5-mile reserve), meaning a strong emergency ConOps must be defined in order to implement emergency procedures and monitoring.

In case of an emergency on airport ground, airport fire station personnel are trained to respond to the specific types of aircraft that land at their airport. Being knowledgeable in the design of these aircraft make them better equipped to avoid more damage to humans or equipment. With the increased number of new vehicles becoming available, a system must be implemented to keep this information up to date so firefighters have constant access to the most accurate database and can train accordingly.

Cybersecurity could be one of the biggest hazards or obstacles to integrating operations. The security of these aircraft systems, capabilities of passengers, and preventative measures are still unknown and could present risk to passengers and individuals on the ground. Remote hacking is also a possible hazard. Other hazards caused by lower-altitude flights in an urban area will arise, such as building interactions, shorter response window, and wake turbulence. The latter will also affect operations at airports. Separation time may need to be adjusted to allow traditional operations and UAM operations to safely coexist. In terms of separation assurance, a risk assessment needs to be conducted to look at the integration of multiple automation systems. UTM separation is done by volume control. Before takeoff, a volume of the airspace is reserved and checked for any conflict with another portion of airspace reserved for another vehicle. Questions remain concerning how strategic and tactical tools will be used to achieve reliability of the overall system. Given the nature of on-demand service, new tools may need to be developed to ensure separation in the airspace.

Installing vertiports on top of buildings will restrict the available space, thereby restricting the number of aircraft able to operate within that airspace. The ability to define alternates is important, as well as the ability to leverage general aviation airports for UAM operations. Some drone programs can geofence, which means that in the event of a catastrophic failure, they would be able to do so in a defined area.

5.2.5 Weather

While it is evident that weather will have a strong impact on UAM operations and vertiports, the extent of the disruption and ensuing mitigation strategies are still unknown. These uncertainties in weather impacts may hinder UAM’s ability to increase operations and safely meet demand. Interviews highlighted that weather patterns in many metro areas could cyclically halt UAM flights. Depending on the season, cities like Dallas and Atlanta have frequent afternoon thunderstorms, which will likely ground UAM vehicles. If regular weather disruptions occur during commuting hours, delays and cancellations will create a self-reinforcing cycle that puts the scalability of UAM at risk.

Without a ConOps for ground operations or the configurations of vertiports, weather impacts on the ground remain a gap with strong implications. Weather will affect vertiports with increasingly higher vulnerability, as the density of the configuration increases. Wind direction may affect the path for the approach stage of the flight cycle, forcing vehicles to fly over people or gates during the vertical stage of landing, the riskiest phase for eVTOL vehicles.

Mission planners and scheduling bodies must learn the proper methods to account for weather. Without granular weather observations, analyses, and forecasts, UAM operations and routes lose flexibility, hindering the scope and scale of flights. High-accuracy, multi-hour forecasts will also be critical for decision making. These forecast models must be accurate and reliable to enable users to depend on them for future integrated operations. The gap in hourly weather forecasting runs the risk of abrupt delays and cancellations, leading to frustrated users who may revert to other forms of mobility.

6 Discussion and Future Research Priorities

ATM-X Phase 3 IR sessions affirmed the potential for successful integration of UAM into the NAS, while identifying key challenges facing full-scale adoption. The literature review, NASA expert interviews, and virtual seminar sessions all indicated that initial UAM demand can potentially be integrated into the NAS, leveraging traditional operations methods and infrastructure. While the identified gaps in vehicle capabilities, routing, WTO, noise mitigation, scheduling of operations, and the role of controllers in managing UAM operations still need to be further researched, the existing airspace infrastructure could accommodate early low-scale operations. However, the “initial” operation numbers that SME’s refer to are still uncertain. While timelines have been investigated, the number of operations that would break the current NAS paradigm has not been identified. Current systems such as TFMS, TBFM, and TBO can be leveraged to form the foundation for gate-to-gate scheduling but will likely require further iterations and research as vehicle capabilities and demands become clearer. A strong, well-defined ConOps will address challenges and opportunities for effective UAM operational frameworks. Vast opportunity exists in designing ConOps for air, ground, and UTM operations, and future research will add granular information to the decision-making process.

Some of the largest obstacles to UAM integration include WTO strategies, noise impact mitigation, and the ensuring collective behavior of heterogeneous autonomous, remotely-piloted, and human operated systems. Future research must consider all these barriers to implementation and scaling to accurately refine the ConOps for vehicle configuration and air and ground operations. Existing mission planning and scheduling software with contemporary UTM constraints and autonomous inputs can help operators manage the airspace, but vehicle capabilities, safety, and public perception must first be characterized.

Vehicle technology for new entrants may change operational risk profiles. Unlike traditional aviation vehicles, eVTOL will be susceptible to the impacts of lightning and lower-intensity winds. Vehicles will likely be electric and may be more susceptible to impacts from lightning on avionics and propulsion systems. Motors, batteries, and wiring may also be affected, impacting vehicle propagation. Although the community realizes wind will be more challenging than with traditional planes, the heterogeneity of vehicles combined with microclimates in urban areas (e.g., turbulent wakes around and between buildings) and a lack of ground and air ConOps make WTO a large, unknown variable. Without previous UAM pilot programs providing lessons learned and a strong ConOps, early UAM operations will likely be confined to areas with benign, low-impact weather. Computational Fluid Dynamics (CFD) models can help provide more insight into the granular interactions that occur in cityscapes. The fidelity provided by CFDs can improve understanding of the nuanced weather impacts and behaviors that would affect UAM operations in high-density markets.

A common framework or understanding of WTO is also needed for future operations. Currently, methods used by operators to determine weather impacts or suitability for operations vary. This can lead to several different determinations of what weather is impactful. The creation of a common framework and method for determining weather suitability would help create a common language and decision-making process when determining WTO. In addition, as automation increases, weather data and tools have the potential to directly and autonomously integrate into flight planning. This provides an opportunity to utilize artificial intelligence (AI) and machine learning (ML) to digest and learn from past weather events and patterns to help form successful decisions around inclement weather. While currently humans remain in the loop, increasingly greater levels of automation could reduce operator workload and improve consistency.

Different vehicle configurations could have vastly different noise characteristics, even when vehicles look alike. While sound dispersion currently exists in traditional operations, utilizing these practices in UAM will need to be further explored. Fleet mixing could also be further investigated to help manage the noise volume and impact of UAM vehicles, as combining different vehicle profiles and noise output may help disperse and balance the noise perceived from these operations. It is important to prioritize the assessment of noise impacts to ensure a successful UAM integration in the public sphere. The IR seminar participants noted that high demand for UAM will correlate with times of high ambient noise in urban areas. This opens up an area for future research to identify ways to blend the noise associated with UAM into the ambient noise to help mitigate the perceived impact

Noise may also be a scapegoat for other concerns, such as safety. It is likely easier to claim noise as a nuisance than to express safety concerns or annoyance at luxury services. Visual noise will play into public perception too. While audible vehicle noise may be mitigated and reduced to below established thresholds, the public may still grow tired of the constant visual presented by operations. Understanding the public's tolerance for visual noise can also help mitigate the community impact from operations.

Public acceptance of AAM will likely drive its adoption. In addition to mitigating concerns over noise, safety, and cost accessibility, galvanizing demand through effective communication and messaging will keep flights full. eVTOL are uniquely positioned in aviation to provide a host of energy and environmental benefits to areas that adopt UAM. In the same manner as electric passenger cars such as the Nissan Leaf, Chevrolet Volt, or Tesla Model 3, eVTOL aircraft will centralize emissions from dispersed tailpipes and aircraft to generating plants in the energy production sector. Centralized emissions allow for measures such as carbon capture and sequestration technology and a cleaner fuel mix to contribute to reduced overall emissions. As of April 2020, the Pew Research center estimates that 74 percent of U.S. adults agree that "the country should do whatever it takes to protect the environment." The transportation sector accounts for about 30 percent of annual greenhouse gas (GHG) emissions (EPA 2017) with aviation responsible for 12 percent of transportation source emissions (ATAG 2020), despite representing a small fraction of transportation volume. Therefore, future research analyzing the energy and environmental benefits and impacts on GHG emissions will help to understand environmental benefits and increase public perception to create a robust market for AAM travel.

Another factor unique to eVTOL vehicles will be the increased burden on the electric grid. As both electric cars and eVTOL aircraft increase scale and density, their massive energy requirements will shift from petroleum-based fuels to the grid. Assessing grid load impacts of eVTOL charging will be necessary for feasible scaling of eVTOL operations. In 2016, U.S. airline operating equipment consumed 17.7 billion gallons of fuel (EIA 2017) or 700,294 GWh of energy, which is about 3.6 times more energy than the total electricity generation of the state of California in 2018 (California Energy Commission 2020). If AAM operations scale to the level that industry hopes, grid load impacts must be addressed. Future research must consider the effect of vehicle charging on both base and peak grid load, as well as on generation and transmission infrastructure.

Finally, as these new technologies and systems emerge, varying regional challenges and obstacles must be better understood before they are adopted nationwide. Research has focused on select, key areas such as the Northeast corridor, Dallas Fort Worth metro area, and California. However, these findings may not be fully representative of all the challenges that other geographies with different characteristics (e.g., weather, demand, infrastructure, airspace configuration) will face. Because of the potential constraints in some areas, operations will likely start in areas with benign weather, favorable airspace and infrastructure, and minimal noise implications. Future research should investigate these obstacles facing a system-wide application of ATM-related systems, procedures, and technologies.

Table 9 lists several key areas of future research for ATM-X. NAS stakeholders and NASA SMEs believe prioritization of these areas will help to implement integrated operations in the future airspace.

Table 9. Summary of Future Research Priorities

Category	Description
ATM	ATM tools and methods require more research before a robust ConOps can be implemented. Autonomous and remotely piloted operations will require fast information sharing and reliable communication between human and non-human agents. Future research should focus on communication links between aircraft and ATC, in addition to information flows between human and machine agents.
	Additional tools are needed if ATC is expected to handle UAM routing (both dynamic and static). Future research is needed for tools to meet mixed equipment and varying traffic flows to fully utilize Performance-Based Navigation.
	Uncertainty surrounding off-nominal (or atypical) situations needs future research. If an ATC loses connection to one or multiple aircraft, autonomous vehicles need the proper capability and defined procedures for safely responding. ATM's ability to handle uncertainty associated with off-nominal situations is key for autonomous new entrants to the airspace.
	NASA SMEs and NAS stakeholders assume that the current ATM paradigm will handle the “initial” scale of UAM operations. As scale increases, ATM becomes exponentially more complex. However, no threshold or estimate for initial operations has been established. Future research must focus on the size of initial operations and study the system break point where new ATM strategies must be employed.
Weather	IR participants indicated that future priorities and research should be placed on constructing a common methodology or approach for operators to determine the weather impacts to their operations. Currently, airlines, individuals, and other operators are left to their own devices and methods when determining weather impacts on their flights. Creating a consistent, replicable approach for all operators would create a common understanding of weather impacts on the NAS on any given day.
	We still do not understand what weather thresholds will be deemed impactful for future operations. While using traditional operations and helicopter operations as a starting point is a good start, passenger comfort and perception when in UAM during inclement weather is still unknown and must be better understood.

Category	Description
	Utilizing AI and ML to aid in the automation and integration of weather into decision making and flight planning can help create a framework for consistent operational decision making. In addition, it can help reduce workload and create a common understanding of impactful weather for integrated operations.
Noise/Public Perception	Aircraft design was identified and agreed as the root cause of noise impacts and public disturbance due to integrated operations. While ways to mitigate the impact of noise from these operations were identified and methods of dispersion were explored, reducing the amount of noise generated due to the aircraft design should be the priority. This can help alleviate the reliance on mitigation techniques and reduce the strain on managing operations to reach a noise threshold.
	In addition to aircraft sound, visual noise will also play a role in public perception. Regardless if people can hear the vehicles, many will likely take issue with constantly having to look at them. Future studies must evaluate visual noise and mitigation strategies to avoid negative public perception.
Human Factors	In the beginning of UAM integration, workload will likely remain high due to the likelihood of exponential traffic growth. New UTM tools will need to be a major part of future research efforts and should aim to reduce human operator involvement and increase automation. Further research should also look at how manned commercial traffic and unmanned automated vehicles will share airspace and runways. The airspace immediately around airports and urban vertiports will need to be subject to redesigning, perhaps using current VFR air taxi service in the New York City area given its similarity with UAM in terms of operational model and workload. Another potential area of future research relates to characterizing the motivation for TOS participation by airlines. Several recent ATM-X studies revealed that delays can be reduced through even minimal TOS participation, which could motivate early adopters. Further research and coordination with airlines to understand their perspective on TOS participation would be beneficial to assess systems and human factors components in their decision-making as part of CTOP.
Safety	Procedures and responsibilities have remained largely the same even with the development of new tools and methods like TBO, because the safety case has yet to be developed. NextGen has helped develop new technologies but lacks procedures to include them into safety analyses. IR participants suggested that future NASA research should focus on providing data and rationale to support the safety case, to allow procedures to be modified.
	Questions remain concerning how strategic and tactical tools will be used to achieve safety and reliability of the overall system. Procedures for separation assurance, right of way, and transition between automated systems and humans in case of emergency have yet to be defined.

Category	Description
	Communication needs to be established between UTM and FAA systems, so vehicles share information with one another. Identifying and standardizing sensors that detect information to be shared with other NAS occupants will also be critical in automating landings. Possible hazards to prepare for could include cybersecurity or remote hacking. Other obstacles will arise due to the new urban environment in which those vehicles will operate, such as building interactions, shorter response window, and wake turbulence, among others.
	Vehicle limitations and operational performance desires are still unknown for UAM. Understanding vehicle performance will help guide tactical separation capabilities as well as routing options and limitations. Vehicle performance will also help inform and uncover what weather is truly impactful to operations and what limitations are presented by different weather thresholds.
Ground Operations	Ground operations are still a gap. Research must be done to maximize efficiency on the ground to limit delay, maximize space, and ensure safe takeoff and landing corridors and zones.
Others	Grid load impacts of eVTOL charging must be accounted for. As energy requirements shift from liquid petroleum fuel to electricity, increased stress will be placed on generating and transmission infrastructure. Understanding the grids ability to handle increased base and peak load from eVTOL vehicles will be critical to large-scale operations.
	Environmental benefits from electric drive trains should be investigated to enhance public perception. A majority of Americans value environmental protection and sustainability. Quantifying benefits by studying the impacts of centralizing emissions to power-generating resources and of displacing internal combustion engine vehicles on the ground will help to incentivize ridership and create a more robust market.
	Determining how individual UAM market segments will grow will be critical to assessing timelines and scale of operations. Determining if specific market segments, such as cargo delivery, air ambulance, and human transportation, will dominate and how they will grow will be necessary to create a strong ConOps for new entrants and AAM.

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14. ABSTRACT

The focus of this final Air Traffic Management – eXploration (ATM-X) Insight Assessment (IA) report is to summarize key findings, lessons learned, gaps, and shortfalls from 2018 to 2019 National Aeronautics and Space Administration (NASA) ATM-X research and to share the outcomes from National Airspace System (NAS) stakeholder discussions with the broader community. This report was generated from a comprehensive review of 25 NASA ATM-X research papers and augmented by interviews with 23 NASA researchers as well as three virtual seminars discussing the project findings and priorities with 47 NAS stakeholders. While these papers cover a wide range of relevant topics, they only represent a small portion of the vast amount of ongoing research in this rapidly evolving area by industry, academia, and other agencies. The research summary described here could be further refined and expanded by reviewing additional studies.

15. SUBJECT TERMS

National Airspace System (NAS), Air Traffic Control (ATC), Air Traffic Management (ATM), Urban Air Mobility (UAM), Unmanned Aircraft System (UAS), UAS Traffic Management (UTM), Advanced Air Mobility (AAM), Concept of Operations and Mission Planning, Weather and Noise Impacts, and Human Factors and Safety and Emergency Protocol

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