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Identify Models for Advanced Air Mobility (AAM)/Urban Air Mobility (UAM) Safe Automation

Task 4: Final Report

January 31, 2025

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16. Abstract
The focus of this project is on Urban Air Mobility (UAM) operations using Uncrewed Aircraft Systems (UAS) for Urban Air Mobility. Such operations are expected to involve significant amounts of automation, including automation to enable and support management of the remotely piloted aircraft by the pilot and to help ensure safety relative to Federal Aviation Administration (FAA) policies regarding the safety continuum. This report summarizes the findings of three previous reports for this project. It also provides specific recommendations to address gaps in the design and use of technologies to support UAM, highlighting those that involve automation to ensure safety. In addition, based on an analysis of the need for standards, a quantitative scoring methodology was developed and applied to provide a clear roadmap for prioritizing the need for standards development across key areas, offering actionable guidance for the FAA to focus future research and standards coordination efforts.

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AAM	Advanced Air Mobility
ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependent Surveillance-Broadcast
AI	Artificial Intelligence
ASQ	American Society for Quality
ASSURE	Alliance for System Safety of UAS through Research Excellence
ATC	Air Traffic Control
ATCT	Air Traffic Control Tower
AWOS	Automated Weather Observing Systems
BVLOS	Beyond Visual Line of Sight
C2	Command and Control
CAST	Causal Analysis based on System Theory
CNS	Communication, Navigation, and Surveillance
CONOPs	Concept of Operations
CPU	Central Processing Unit
DAA	Detect And Avoid
DDC	Dynamic Delegated Corridor
DT	Decision Tree
ERAU	Embry Riddle Aeronautical University
ETA	Expected Time of Arrival
eVFR	Enhanced Visual Flight Rules
eVTOL	Electric Vertical Take-Off and Landing
FAA	Federal Aviation Administration
FCP	Flight Control Processor
FMEA	Failure Mode and Effects Analysis
FOC	Flight Operations Center
FRAM	Functional Resonance Analysis Method
GNC	Guidance, Navigation, and Control
GPS	Global Positioning System
GPU	Graphics Processing Unit
GNSS	Global Navigation Satellite System
ID	Influence Diagram
IFR	Instrument Flight Rules
IP	Internet Protocol
KSU	Kansas State University
LC2L	Loss of Command and Control Link
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NOTAM	Notice to Airmen
OFF	Wheels Up
OSU	Ohio State University
PIC	Pilot In Command
PSU	Provider of Services to UAM

RA	Resolution Advisory
RNP	Required Navigational Performance
RPIC	Remote Pilot In Command
RPN	Risk Priority Number
RTCA	Radio Technical Commission for Aeronautics
SIDs	Standard Instrument Departure
SME	Subject Matter Expert
SRA	Safety Risk Analysis
STAMP	System-Theoretic Accident Model and Processes
STAR	Standard Terminal Arrival Route
STPA	System-Theoretic Process Analysis
TA	Traffic Advisory
TBFM	Time Based Flow Management
TCAS	Traffic Collision Avoidance System
TFM	Traffic Flow Management
TFR	Traffic Flow Restriction
TMF	Traffic Management Function
TMI	Traffic Management Initiative
TSO	Technical Standard Orders
UAM	Urban Air Mobility
UAS	Unmanned Aircraft Vehicle
UND	University of North Dakota
VDL2	VHF Data Link Mode 2
VFR	Visual Flight Rules
VHF	Very High Frequency
VTOL	Vertical Takeoff and Landing

EXECUTIVE SUMMARY

This is the final report for Phase 4 of the project titled "Identify models for Advanced Air Mobility (AAM)/Urban Air Mobility (UAM) safe automation." It provides recommendations for ensuring safe automation to support UAM operations, as well as a description of findings supporting these recommendations. Additional detail is available in the Phase 1 report regarding the relevant literature, in the Phase 2 report regarding approaches to risk assessment, and in the Phase 3 report on the design and use of supporting automation technologies as well as relevant standards, regulatory processes, and policies. The primary focus of these four reports is on UAM operations with remote pilots with moderate to high traffic density.

For this analysis, the evolution of UAM is assumed to be broken up into four stages:

- **Initial UAM Operations Phase 1:** Electric Vertical Take-Off and Landing (eVTOL) vehicles are utilized in UAM operations with the Pilot In Command (PIC) onboard, flying under current regulations and procedures.
- **Initial UAM Operations Phase 2:** eVTOLs are utilized in UAM operations flown by Remote Pilots In Command (RPICs) under current regulations and procedures that apply to legacy operations (such as those with helicopters). There continue to be flights with onboard pilots as well.
- **Midterm UAM Operations:** Increased volume could necessitate the introduction of structured airspace for UAM operations. This analysis assumes that such structured airspace is introduced for Midterm Operations and that more comprehensive preflight deconfliction is introduced. However, given the regulatory hurdles and operational requirements associated with creating such structured airspace, it is possible that Midterm Operations will continue to simply rely on charted routes as the mechanism to provide structure to traffic flows. eVTOLs are flown by RPICs. There continue to be flights with onboard pilots. Each RPIC is responsible for a single aircraft. Increased automation is necessary to support flying the remotely piloted aircraft and could support reduced separation.
- **Mature UAM Operations:** Structured airspace remains necessary for UAM operations. eVTOLs are flown by RPICs. There continue to be flights with onboard pilots. For some operations, a multi-aircraft supervisor is responsible for several aircraft. Even more automation is necessary to enable this, as well as organizational design that ensures safe operations when significant off-nominal scenarios arise.

In the body of the report, a significant number of specific recommendations are made regarding the need for additional research, development, evaluation, risk assessment and standards development for technologies to ensure the safe operation of eVTOLs by remote pilots for UAM operations. The focus of these recommendations includes technology support for weather decision-making by flight planners at flight operations centers, by remote pilots and by flight managers at vertiports and Providers of Services for Urban Air Mobility, as well as traffic managers and air traffic controllers at airport towers. This includes technology to support the use of UAM aircraft as sensors, providing networked access to integrated data displayed in a manner that supports

effective decision-making by this full range of users. Meteorologists with expertise in UAM operations agree: "For operations starting in the next 2-4 years, we are not well prepared."

As another example, the recommendations include a focus on traffic flow management, designing the system to manage the air traffic so that DAA technologies are needed by exception as a reactive safety net, rather than assuming that their activation will be routinely required. And another example of a focus area is on recommendations prioritizing the need for specific standards for the implementation of UAM, providing a clear roadmap for standards development across key areas and offering actionable guidance for the FAA to focus future research and standards efforts.

The section on Conclusions then provides a high level summary of research areas that need to be addressed in order to inform the design and use of automation to support safe UAM operations. These research needs are categorized in terms of:
- Separation assurance.
    - DAA.
    - Return to mission.
    - DAA for autonomous control by aircraft.
    - Traffic flow management.
- Effective design of digital infrastructure for vertiports.
- Weather decision making.
- Communication.
- Risk Assessment.

Appendix A lists the recommendations that have been developed concerning the development and use of technologies to provide safe automation that need to be addressed in the transitions from Initial to Midterm to Mature Operations. These recommendations regarding the development and use of technologies to support safe automation are discussed in more detail in the body of the report.

Appendix B provides the results of applying a quantitative scoring methodology to provide a clear roadmap for prioritizing the need for standards development across key areas, offering actionable guidance for the FAA to focus future research and standards coordination efforts.

These discussions serve to emphasize that the design of safe automation requires thinking beyond safety at a component level to address safety from a system design perspective. Thus, the discussions range from technology concerns in the design of software to support detect and avoid and the development of procedures and supporting automation to ensure strategic deconfliction at a systems level.

1.0 INTRODUCTION AND OVERVIEW

This project focuses on the development of recommendations regarding safe automation for the support of Urban Airspace Mobility (UAM). The goal of this report is to capture the important findings in the reports from three previous tasks into a final report package for the overall project.

Rather than providing a brief summary of these reports and referring the reader to the previous three reports produced by this project, the approach taken has been to produce a standalone report that describes the conclusions and supporting rationale for these conclusions. It does so by incorporating content from these previous reports and providing specific associated recommendations for the FAA and standards development organizations.

These three previously completed tasks with associated reports have been:
- **Task 1: Background Report**. This task focused on a literature review to avoid duplication of effort and to provide insights into potential failure stories and mitigations. The literature review included consideration of UAM automation, human-automation interaction, aircraft system architectures and concepts of operation, as well as standards, regulations, certification, and policy. It included academic, government, standards development organizations, and industry sources.
- **Task 2**: **Risk and Technology Assessments.** Informed by the results of Task 1, a study was conducted to consider approaches for risk assessment. The results associated with one such method were then illustrated.
- **Task 3: Forming Recommendations.** Gaps and roadblocks to realizing future UAM operational capabilities were then identified. This included consideration of both technologies and procedures. It also included consideration of standards development.

1.1 Timeline for the Evolution of UAM

The analyses discussed in the previous reports divided the timeline for UAM into four phases:

- **Initial UAM Operations Phase 1:** eVTOL vehicles are utilized in UAM operations with the PIC onboard, flying under current regulations and procedures that apply to legacy operations (such as those with helicopters).
- **Initial UAM Operations Phase 2:** eVTOLs are utilized in UAM operations flown by Remote Pilots In Command (RPICs) without a safety or secondary pilot onboard, flying under current regulations and procedures that apply to legacy operations (such as those with helicopters). There continue to be flights with onboard pilots as well. Given the regulatory hurdles and operational recommendations associated with creating structured airspace, depending on volume and complexity, it is likely that Initial Operations Phase 2 will continue to simply rely on the designation of unstructured Visual Flight Rules (VFR) airspace for UAM aircraft or VFR airspace with structured routes. Each RPIC is responsible for a single aircraft. Increased automation is necessary to support flying the remotely piloted aircraft.
- **Midterm UAM Operations:** Increased volume necessitates the introduction of structured airspace for UAM operations and that more comprehensive preflight deconfliction is introduced. Each RPIC is responsible for a single aircraft, and there continue to be flights

with onboard pilots. Increased automation is necessary to support flying the remotely piloted aircraft through the structured airspace and could support reduced separation.

- **Mature UAM Operations:** For some operations, a multi-aircraft supervisor is responsible for several aircraft. Even more automation is necessary to enable this, as well as an organizational design that ensures safe operations when significant off-nominal scenarios arise.

The primary focus of the analysis is on operations with remote pilots, which begins with the Initial UAM Operations Phase 2.

These stages are consistent with Federal Aviation Administration (FAA) UAM Concept of Operations (CONOPs) V2 (FAA 2023a), except that Initial UAM Operations are divided into two phases, as shown in Figure 1.
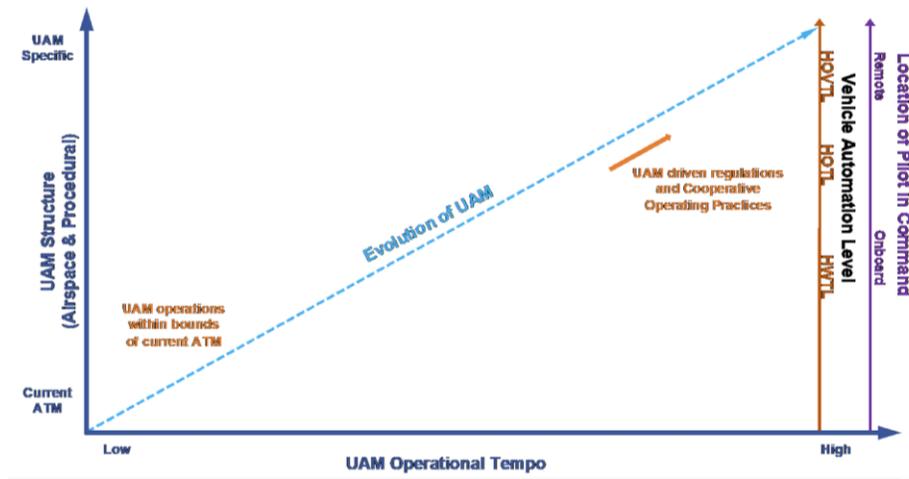
Figure 1. Evolution of the UAM Operational Environment (from FAA 2023a).

1.2 Roles

Keeping in mind that some individuals will play multiple roles depending on the size of the flight operations, the following roles are relevant to one or more of the time frames:

- Provider of Services to UAM (PSU) flight manager (Boeing 2023; ASTM 2022).
- Meteorology expert.
- Vertiport flight manager.
- Vertiport ground support.
- Dispatcher/flight planner.
- Aircraft scheduler (out of scope for A64).
- Pilot/crew scheduler (out of scope for A64).
- RPIC or onboard Pilot in Command (active PIC or safety PIC).
- Visual observer.
- Maintenance technician.
- Helicopter operators.
- Local law enforcement.
- FAA Air Traffic Control (ATC) / Traffic Flow Management (TFM).

- Other operations management staff for flight operators.

1.3 Assumptions Relevant for Various Time Frames

The following are assumptions made that apply to all time frames. Assumptions relevant to a specific timeframe (Initial, Midterm, or Mature Operations) will be indicated as part of the discussion of that timeframe.

- Convective weather storms, winds, and winter weather are possible.
- Except for altitude profiles for departures and arrivals, UAM aircraft fly between 500 and 4000 ft. There may or may not be specified Standard Instrument Departure routes (SIDs) and Standard Terminal Arrival Routes (STARs).
- All UAM aircraft are eVTOL rotorcraft. While this analysis focuses primarily on such eVOL aircraft, hybrid aircraft and non-eVTOL platforms could be part of the mix in the future as well. (Many or the recommendations apply to these aircraft as well.)
- There may be a mix of UAM aircraft that are remotely piloted and aircraft that have a pilot on board.
- UAM flights can carry cargo or passengers.
- Contingency plans for flight include consideration of factors that could impact the airspace capacity or the capacity of a vertiport, such as convective weather impacting vertiport airspace, availability of landing pads at a vertiport due to factors such as weather, incapacitated aircraft on a landing pad, availability of ground personnel, etc.
- In addition to alternate vertiports for diversions and designated ditch sites specifically designed for UAM landings, emergency alternate landing sites have been identified for each flight. These could be at an airport, sports field, park, etc. Use of the latter is coordinated with local law enforcement and ATC as necessary and possible

2.0 TECHNOLOGY GAPS: RECOMMENDATIONS APPLICABLE ACROSS ALL PHASES OF EVOLUTION OVER TIME

There are certain recommendations focused on automation that can impact safety and that apply regardless of whether there is a pilot on board (Initial Operations Phase 1a) or a remote pilot (Initial Operations Phase 1b, Midterm Operations, and Mature Operations). Therefore, these are highlighted before discussing these phases individually. It should be noted that these recommendations become even more important as traffic volume and complexity develops and as reliance on automation for the control of trajectories increases.

2.1 Support for UAM Weather Decision Making

Interviews with three expert meteorologists, all of whom have been involved in research, development, and testing relevant to UAM operations, provide a very strong caution regarding the need for adequate support for weather decision making for flight planners, flight followers, Air Traffic Control Tower (ATCT) Traffic Managers, controllers at an AAM (Advanced Air Mobility) position, vertiport flight managers and pilots. One of these Subject Matter Experts (SMEs) is also an expert in the performance of Guidance, Navigation, and Control (GNC) models relative to wind fields and storm activity. These three SMEs offered expertise regarding meteorology (convective weather and winds) as it pertains to the operation of UAM.

From an automation perspective, this relates to technology to support weather sensing and modeling, and the translation of meteorological input to support preflight and real-time decision making. Concerns include wind flows, convective weather and turbulence: "Thunderstorms create a whole set of hazards: Wind and wind gusts, turbulence, hail, icing, lightning, microbursts. You need to monitor for short term changes."

These meteorologists all emphasized that convective weather and winds in the lower altitudes of urban areas have spatial and temporal features that are different from higher altitude weather patterns and flows. They also indicated that there are many urban areas where these lower altitudes are not currently well equipped for weather sensing. And they noted that, although Unmanned Aircraft System (UAS) flights may be relatively short, such as 20 minutes in duration, unexpected convective weather and winds can develop in that time frame, indicating: "Unexpected storm motion and intensity can arise, especially if there is already some activity in the vicinity."

To summarize the urgency associated with such research, development, and testing, one meteorologist noted: "For operations starting in the next 2-4 years, we are not well prepared."

2.1.1 Access to Weather Data.
To provide the data needed to support weather decision-making, the meteorologists indicated that increased access to weather sensors in these urban areas is important. In particular, they indicated that, to provide adequate weather data to support UAM weather decision making, there is a need to equip drones used operationally as weather sensors and to share these data over a network, both to provide reliable data for providing more accurate weather models as well as to support real-time decision making. ("You need to be monitoring changes in conditions while airborne to decide whether to continue or abort. If a storm is evolving nearby, you need to start paying attention to it.") Such sensors need to provide data about convective weather, wind fields, and turbulence.

In addition, they emphasized that weather models need to be developed in general and for specific urban areas to support the development of weather forecasts: "The weather data and information need to guide decisions about what to do in the next half hour. Do we abort? Do we change our flight plan?"

Weather data focused on the surrounding area also needs to be incorporated into the development of such forecasts to look ahead over time: "Flight planning needs to have a good forecast. You need real-time high-resolution forecasts." Now-casts are necessary as well.

2.1.2 Weather Information Integration and Display.
These weather experts highlighted the need to integrate the firehose of weather information into the design of effective displays to support decision-making. ("We don't understand sensor fusion well enough yet.") Such design efforts need to take into consideration the different needs of the full range of decision makers and the different look-ahead times that they need to consider.

2.1.3 Technology Required to Support Increasingly Automated Aircraft.
The transition to remote pilots is expected to result in increased reliance on onboard automation for tactical responses to enroute weather. This becomes even more important if, as is proposed for mature operations, one

pilot is managing multiple aircraft. As one of the meteorologists indicated, this increases the automation required:

> "You need onboard microscale simulations to provide sufficiently fast computations. … An example of this is provided by FastEddy, a resident-GPU [Graphics Processing Unit] model, meaning that all prognostic calculations are carried out in an accelerated manner on GPU with CPU [Central Processing Unit] utilization strictly limited to model configuration and input/output of modeling results. This resident [onboard] GPU approach shows tremendous early potential for achieving faster-than-real-time microscale simulations … that can support tactical responses to the weather" (NCAR, 2025).

2.1.4. Weather Decision Making: Recommendations.
The importance of the conclusions summarized above was indicated by the meteorologist who is also an expert in GNC for UAM aircraft. He indicated that poor weather decision-making (go/no go decisions both preflight and while enroute, as well as diversion decisions while enroute) *is more likely to result in incidents* than a lack of increasingly adaptive GNC systems. He noted that: "It is not sufficient to rely on reactive robust aircraft control systems to ensure safety. Such technologies may handle 95% of the situations that may arise, but significant risk remains with that approach alone … They can make control more robust, but they can still be overwhelmed … Robust controllers can be lost in the noise … [meaning that these technologies] won't solve the problem of a lack of adequate predictability to decide to launch."

This concern was reinforced by a second meteorologist: "The level of understanding of weather at the level of granularity required for urban UAS operations is still limited. This lack of knowledge could contribute to operational failures if not resolved."

Thus, there is a significant need to research, develop, and test weather technologies, including on-board radar with weather, Air-to-Air, Air-to-Ground, Ground-to-Air and Ground-to-Ground capabilities.

Note that the recommendations in blue indicate areas with implications for safety automation that require attention from the FAA and/or standards organizations in terms of research and standards.
- Recommendation 2.1: The sensors and automation necessary to provide good, actionable convective weather and wind information for operators to make preflight decisions about proceeding with a mission, planning a route, or diverting a flight while enroute need to be further developed and tested.
  This includes the need to support networked access to data provided by drones as weather and wind sensors, and the need to develop automation to integrate and display these weather data effectively to support weather decision-making by the full range of users. The information display requirements will vary depending upon the specific user (such as an air traffic controller vs. a remote pilot).
  This also includes the need to develop weather models for urban airspace that provide forecasts based on all of the available weather data.
- Recommendation 2.2: Standards need to be provided for weather sensors and their housing on UAM aircraft, as well as weather modeling techniques.

- Recommendation 2.3: In addition to providing the technologies necessary to support improved weather decision making, UAM safety can also be enhanced by improvements in GNC robustness to better respond to "very windy conditions."
- Recommendation 2.4: As the degree of tactical control by aircraft automation increases to better support remote pilots, onboard automation to assess and generate responses to real-time weather and winds becomes increasingly important and needs to be further developed and tested.

Finally, it is important to note that the cost of inadequate support for weather decision-making is not only an increased potential for incidents affecting safety, but it also has the potential to lead to unnecessarily conservative launch decisions (which may be desirable for initial operations). As indicated in the interviews:

- "For UCLA Health, the primary concern is knowledge of weather conditions at the landing site. In particular, many air ambulance flights are called off ... to the detriment of patients with critical health problems ... due to uncertainty of weather conditions at the landing site."
- "At the time a go/no go decision has to be made, if there isn't sufficient information, the PIC/RPIC and FOC [Flight Operations Center] will have to err on the side of caution."

2.2 Traffic Flow Management

Whether there is an onboard or remote pilot, for higher volume and complexity operations that involve adherence to a schedule, will need an increased level of coordination, including support by a reservation system and a process for clearance to depart that considers the expected demand and capacity for the arrival and enroute airspace, as well as the availability of the planned landing pad, including the availability of a backup or emergency landing pad. Depending upon the airspace classification and supporting automation, such scheduling may introduce responsibilities for a PSU or ATCT Traffic Manager or both.

Responsibilities for TFM (ASTM WK85415, 2023; Unmanned Space, 2025) will also require procedures and supporting automation to ensure safety by managing traffic in the face of uncertainties arising from convective weather and winds. The necessary degree of coordination with other airborne UAM aircraft, the vertiport, and the ATCT will depend on the airspace classification when departing or landing at a vertiport or landing site. It will also depend on flight volume and complexity.

As an example, if a private vertiport is supporting cargo operations, the vertiport is in Class G airspace and volume is modest, PICs and RPICs may simply need to communicate with the vertiport operator to help ensure the landing pad is clear for arrival and announce their intentions on the relevant Common Traffic Advisory (TA) frequency (or a designated AAM frequency) for that area to coordinate with other flights.

For higher volumes and operations that involve adherence to a schedule, however, an increased level of coordination will be required, including support from a reservation system and a process for clearance to depart that considers the expected demand and capacity for the arrival airspace, as

well as the availability of the planned landing pad. Such scheduling will introduce responsibilities for the PSU, PIC/RPIC, FOC, Traffic Managers at ATCTs, and controllers at ATCTs. TFM initiatives will also be required, similar to but not identical to the use of ground delay programs and ground stops as used for legacy operations today.

In addition, if there is uncertainty regarding weather or wind constraints at the planned destination vertiport, the PIC/RPIC (and supporting flight planner if there is one) will need to plan for one or more alternative vertiports or ditch sites for a diversion and ensure an adequate battery supply. At the time that a diversion becomes necessary, the PIC/RPIC will need to leave the planned VFR route and fly to the diversion landing site. The degree of coordination for this again will depend on the airspace classification and the supporting automation.

Based on the points summarized above and detailed in Report 3 for this project, there are several recommendations for the FAA and other stakeholders with operational responsibilities for UAM flights arriving at and departing from vertiports at airports within Class B, C, and D airspace.

Again, the recommendations in blue indicate areas with implications for safety automation that require attention from the FAA in terms of research and in terms of standards. The assumption is that the most effective way to ensure safety is to manage the traffic through arrival metering and Traffic Management Initiatives (TMIs) such that tactical Detect and Avoid (DAA) responses are usually unnecessary.

- Recommendation 2.5: The FAA needs to designate VFR airspace for flight between vertiports. VFR routes may also need to be designed. (The introduction of VFR routes or corridors requires significant evaluation, however.) Strategies to deal with higher traffic volumes (such as traffic flow management) need to be considered to manage traffic both for the case where such structured airspace is designated and airspace design where it is not.
- Recommendation 2.6: For each urban area, the FAA needs to define the procedures for entering and exiting ATC controlled holding patterns and go-arounds for flights flying in UAM VFR airspace to fly to vertiports. (For diversions that require exiting UAM VFR airspace, procedures similarly need to be defined.)
- Recommendation 2.7: UAM aircraft need to be consistent with the FAA requirements for power-lifted aircraft (FAA Power-Lifted SFAR, 2024).
- Recommendation 2.8: Aircraft certification by the FAA needs to require that onboard avionics safely support PIC/RPIC performance in off-nominal scenarios requiring responses such as entry and exit from a holding pattern, initiation and completion of a go-around, or a diversion. As an example, the FAA needs to determine whether a "go-around" button should be required for a UAS as a safety measure to initiate a missed approach when aborting a landing in favor of a new attempt.
- Recommendation 2.9: The FAA needs to require training for pilots and controllers regarding holding patterns and go-around procedures associated with flights arriving at vertiports at airports in Class B, C, and D airspace.
- Recommendation 2.10: The ATCT Traffic Manager at the arrival airport needs to determine the conditions when UAM traffic volume and complexity increase enough to require arrival metering and TFM initiatives. Assuming these conditions exist:

o The FAA needs to specify the assignment of roles and responsibilities for metering and creating TMIs. At airports in Class B, C, and D airspace, specification of arrival rates for metering and the creation of TMIs will be the responsibility of the ATCT Traffic Manager. The roles of ATCT Traffic Managers, FOCs, PICs/RPICs, PSUs, and vertiport flight managers need to be specified. Supporting procedures and technology required of each group need to be developed.

   For airports and landing sites in Class E and G airspace, the FAA needs to specify criteria and an approval process to evaluate proposed staffing, procedures, and supporting automation.
o Recommendation 2.11: If sufficient volume and complexity exist, the use of TFM initiatives will be required.
o Recommendation 2.12: Automation will be required to manage metering and to create and disseminate Traffic Management Initiatives. This includes automation for the responsible ATCT Traffic Manager to meet the following decision support and TFM requirements:
   ▪ A traffic management display that provides an integrated display of air traffic, weather, terrain, and special use airspace to provide situation awareness and to support decisions relevant to metering of arrivals and the creation of TMIs. For UAM operations, this display needs to provide such information as is relevant to the low-altitude operation of UAM aircraft. The display of information relevant to the bigger picture, including legacy operations, is also necessary to provide situation awareness.
   ▪ Flow Evaluation Areas customized for application to display forecasts of traffic loads over time to make decisions about the management of low altitude operations for UAM aircraft.
   ▪ A decision support tool for the ATCT Traffic Manager that -
      • Allows the ATCT Traffic Manager to set arrival rates for each of the different flows (if there is more than one) feeding the vertiports at the airport and communicating that information to the relevant parties. This could require information from the vertiport flight manager regarding the capacity of a vertiport to accommodate arrival rates based on approach procedures and the number of available landing pads. Arrival rates need to be available for longer-term scheduling purposes as well as real-time updates to manage dynamic conditions on the day of operation.
      • Allows the ATCT Traffic Manager to create and disseminate TMIs, with input from FOCs and vertiport flight managers. PSUs with appropriate automation might support this dissemination.
      • Allows a reservation system manager to translate these arrival rates into assigned release times (OFF times) while also accommodating pop-ups. This will require input from

the flight operators regarding airtimes using automation. The assignment of responsibility for reservations to a PSU or the ATCT needs to be determined.

- Allows a Time-Based Flow Management (TBFM) decision support tool to support reassignment and communication of release times shortly before OFF by the ATCT traffic manager based on actual traffic flows. This requires coordination of both the arrival and departure ATCTs for such rescheduling.

- Recommendation 2.13: For departures controlled by ATC, the release times assigned to individual UAM flights need to be displayed to the ATCT AAM controller.
- Recommendation 2.14: FOCs and PICs/RPICs need a tool that supports the filing and cancellation of flight plans as well as substitutions, etc. This tool also needs to provide updated information on release times.
- Recommendation 2.15: The FAA needs to develop recommendations for the digital infrastructure to complement existing regulations regarding the physical infrastructure for vertiports. This includes recording performance data for post-operation analysis.
- Recommendation 2.16: The FAA needs to develop recommendations for software to support a vertiport flight manager. Specifically, these specifications need to require a ground workstation to maintain situation awareness (weather and traffic), to provide input regarding arrival capacity to the ATCT Traffic Manager when appropriate, and to communicate with ATC, the vertiport ground crew, the PSU if one is established, PICs/RPICs, and FOCs.
- Recommendation 2.17: All stakeholders with operational responsibilities need a tool that displays Notices to Airmen (NOTAMS).
- Recommendation 2.18: In addition to the above recommendations associated with the management of arrivals and departures associated with vertiports at airports in Class B, C, and D airspace, the FAA needs to establish requirements for the operation of private vertiports in Class G and Class E airspace regarding metering and TMIs. (For such vertiports at airports with low-volume operations, the flights may self-separate and sequence using current procedures for helicopters.)

- Recommendation 2.19. For private vertiports at such airports with higher volume, the FAA needs to establish requirements regarding responsibilities and regarding the process and supporting software for managing the sequencing and spacing of arrivals (as contrasted with public vertiports in Class B, C, and D airspace where ATC will be required to flight follow and will have positive control in case of an off-nominal event).

3.0 TECHNOLOGY DEVELOPMENT: INITIAL OPERATIONS PHASE 1 (ONBOARD PILOTS)

For Phase 1, it is assumed that UAM operators are required "to comply with existing Communication, Navigation, and Surveillance (CNS) recommendations for the airspace in which

they will operate" (FAA, 2023b). Below, a discussion relevant to airspace design and the use of automation to support these Phase 1 operations is provided. This section ends with the identification of recommendations that the FAA needs to address.

3.1 Initial Operations Phase 1 (pilot onboard): Airspace Usage and Route Structure

The AAM Implementation Plan (FAA, 2023b) states that, for Initial Operations:

> "AAM operators are expected to comply with existing Communication, Navigation, and Surveillance (CNS) recommendations for the airspace in which they will operate. ... The addition of AAM operations will add to the already busy traffic levels of Class B and C airspace. In cases where existing procedures for Visual Flight Rules (VFR) do not meet the needs of air traffic facilities or AAM operators, special agreements or coordination may need to occur to accommodate increases in traffic levels. Ideally, agreements made at the local level will reduce ATC workload.

> Charted routes [see Figure 2] will be the primary routing structure used by AAM aircraft. This approach enables the FAA to develop routes that accommodate AAM operator needs while leveraging the existing design and charting processes. The development of airspace route structures for I28 operations [FAA Implementation Plan for 2028] will consider design standards based on 14 CFR parts 135 and 91, General Operating and Flight Rules, local procedures, terrain, and traffic flows."
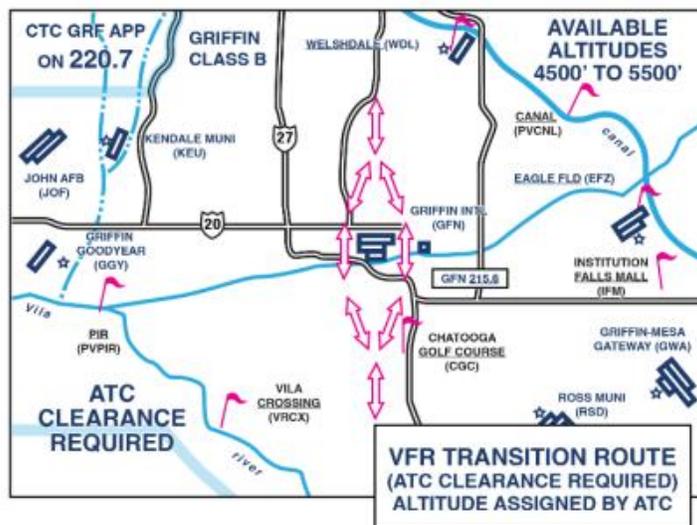
Figure 2. Charted routes for Initial Operations (from FAA, 2023b).

These assumptions are consistent with a recent National Aeronautics and Space Administration (NASA) study of initial and midterm operations:

> "Initial UAM operations are expected to start at a low operational tempo. It is also assumed that airspace operations would be consistent with current-day airspace rules and regulations, and with local letters of agreements in place. Existing air traffic services and routes would be used and new routes would be established only as necessary. Initial UAM operations are also expected to fly with a single, onboard, pilot-in-command (PIC) in the cockpit. Since initial UAM operations will be subject to current-day airspace rules and

regulations, the UAM PIC will be expected to communicate with air traffic control (ATC) to conduct operations in and out of Class Bravo, Class Charlie, and Class Delta controlled airspace in the vicinity of airports" (NASA 2024a)."

Procedures for airborne holding and go-arounds also need to be developed and trained (Lee et al. 2021).

It should be noted, however, that studies defining possible UAM operations for flights into and out of LAX have not indicated the need for charted routes as indicated above. It is likely that, at many of the sites where UAM is established, operations will begin with only the definition of unstructured UAM VFR airspace without charted routes. Charted routes may be introduced as needed as traffic levels increase.

3.2 Initial Operations Phase 1 (pilot onboard): Communication and Coordination

- Consistent with studies focused on arrivals and departures for LAX with onboard pilots, for the development and evaluation of possible airspace design, it is assumed that they will fly VFR through designated airspace within Class B, C, or D airspace, which is likely to have defined routes and procedures, albeit not necessarily published/charted but rather covered in an LOA or something similar. ATC will be:
- Providing clearances for departure and landing.
- Flight following during nominal operation in the enroute portion of a flight.
- Providing active control in off-nominal conditions that require airborne holding, go-arounds or diversions.

Communication will be via radio transmissions.

As noted in an interview with a helicopter operator discussing the current procedures for helicopters that will apply to eVTOLs in Initial Operations Phase 1 when they are not traversing Class B, C, and D airspace:

"The vast majority of helicopters are VFR, and they don't have to really talk to anyone as long as they stay out of Bravo or Charlie airspaces. ... It's really similar to an aircraft flying out of an uncontrolled grass airfield."

"If we are not in controlled airspace, then we'll (optionally) broadcast on the relevant Common Traffic Advisory frequency for that area. If we are in controlled airspace, we will talk to the controller for that airspace. If not required to do so specifically due to airspace and control zones, responsible pilots of helicopters or fixed wings make blind calls of their intentions on the frequency operating in that zone."

3.3 Initial Operations Phase 1 (pilot onboard): See and Avoid

For the Initial Operations Phase 1 with onboard pilots, just as with current helicopter operations, separation assurance is based on 'see and avoid' by the onboard pilots. However, as described below, see and avoid may be supplemented by enhanced capabilities providing enhanced VFR operations, but such additions are not required:

"Joby Aviation and Sagetech Avionics began partnering in 2022 to study the role of on-board piloted Detect and Avoid (DAA) in support of Joby's proposed enhanced Visual

Flight Rules (eVFR) operations. These operations, described in [Radio Technical Commission of Aeronautics] RTCA's DO-398a Operational Services and Environment Document (OSED) as an extension to special VFR (SVFR), would provide earlier warnings of impending close encounters with nearby aircraft and provide maneuver guidance to avoid close encounters entirely, even when the pilot cannot see the neighboring aircraft. In later implementations, eVFR would provide an operating umbrella that improves operational tolerance to weather impacts by lowering visibility and cloud clearance Recommendations.

The core of the eVFR operating capability is the FAA's next-generation collision avoidance algorithm for rotorcraft, [Airborne Collision Avoidance System] (ACAS) Xr. Sagetech's ACAS Xr-based DAA system builds on the foundation of their TSO [Technical Standard Orders] Authorized MXS transponder [a miniature, low-size, weight, and power aviation transponder] for use in crewed and uncrewed operations. Joby continues evaluation and testing of the prototype DAA system in flight and in a lab environment as the system and industry recommendations mature. The goal of the joint effort is to certify a DAA solution that meets the needs of Part 135 eVTOL operations and supports any aircraft that would benefit from operating under eVFR" (Joby 2024).

Use of such capabilities during Initial Operations Phase 1 (onboard pilots) will provide valuable experience for progressing to Initial Operations Phase 2 (remote pilots) when this technology will need to be required.

3.4 Initial UAM Operations Phase 1: Recommendations for eVTOL Operations with Onboard Pilots

The recommendations specified in Section 2.0, which include recommendations directed toward the FAA and standards organizations with implications for safety automation, all apply.

Additional recommendations for the FAA also arise, but these do not have implications for research and standards relevant to safety automation.

- Recommendation 3.1: According to the FAA 2028 Implementation Plan, charted VFR routes, holding patterns, and go-around procedures need to be defined. Simulations studying UAM operations at LAX with onboard pilots, however, have indicated that there will be a need for defined routes and procedures, albeit not necessarily published/charted but rather covered in an LOA or something similar.

- Recommendation 3.2: Procedures need to be developed for the PIC, vertiport staff, and ATC for management of UAM flights that have to deviate from their planned trajectories for diversions, traffic avoidance, and weather. As noted in Section 2.0, such procedures include the responsibility for ATC to control flights that need to be put into holding or need to initiate a go-around.
- Recommendation 3.3: Figure 3 provides a more extensive airspace design that includes a broad area for unstructured VFR airspace around charted VFR routes to reduce the burden on ATC when deviations from the planned route for a flight are required. If volume and

complexity reach sufficiently high levels during Initial Operations Phase 1 (with onboard pilots), it may be necessary for the FAA to develop this type of airspace design to reduce the workload for ATC.

For private vertiports in Class G airspace with low-volume operations, the flights may self-separate and sequence using current procedures for helicopters. For private vertiports with higher volume, the process for managing the sequencing and spacing of arrivals needs to be defined. Those proposed operations will need FAA approval.

Figure 3. Airspace design with charted VFR routes and unstructured UAM airspace (from FAA 2023a).

4.0 TECHNOLOGY DEVELOPMENT: INITIAL OPERATIONS PHASE 2 (REMOTE PILOTS)

This section focuses on Initial UAM Operations Phase 2. The important addition is the introduction of flight operations with an RPIC. As with Initial Operations Phase 1 (with onboard pilots):

> "AAM operators are expected to comply with existing communication, navigation, and surveillance (CNS) recommendations for the airspace in which they will operate" (FAA, 2023b).

It should be noted that, when necessary, there is a precedent under current procedures to include the specification of charted routes and to assign an AAM frequency for communications with ATC, as illustrated by current helicopter operations at Las Vegas International Airport.

In terms of airspace usage and procedures, remotely piloted aircraft will be treated as equivalent to flights with onboard pilots. Issues associated with the use of DAA to support such performance are discussed later. As envisioned in a MITRE use case (MITRE 2019):

"The UAM aircraft gains altitude ... and reaches its cruise altitude of 1,500 feet. The aircraft is equipped with augmented VFR technology and flies a company preferred route towards an established VFR corridor. It uses DAA equipment to avoid other aircraft as if it were like a piloted aircraft following visual flight rules [VFR]. Under the Mode C veil, the UAM aircraft is broadcasting [Automatic Dependent Surveillance-Broadcast] ADS-B. The broadcast includes an indication that the aircraft does not have a human pilot onboard and is using augmented VFR technology."

It should be noted, however, that although the remotely piloted aircraft flies "as if it were like a piloted aircraft," there are significant additional recommendations in terms of technology and procedures to support this.

The FAA needs to establish recommendations for remote pilots of UAM aircraft to be equipped with a ground control station that provides the RPIC (with a separate RPIC for each aircraft in Initial Operations Phase 2) with situational awareness regarding other traffic and obstacles along the planned 4D trajectory (enhanced Visual Flight Rule operations) and with DAA technology. UAM aircraft with a pilot onboard, which can also be operating in this airspace, are not required to be equipped with these technologies. Flights with a pilot onboard that are not so equipped are treated as non-cooperative aircraft by the DAA used by a remotely piloted aircraft.

It is further assumed that demand relative to capacity isn't high enough to necessitate the introduction of the highly structured airspace proposed for the later phases defined by Midterm and Mature Operations.

In addition to defining procedures (such as required separation distances), additional needs to support the safe operation of remotely piloted aircraft are listed below. Items listed in blue indicate recommendations for safety automation. Provide:

- Recommendation 4.1: Software to provide the RPIC with situation awareness regarding other traffic and obstacles in the area (enhanced Visual Flight Rule operations).
- Recommendation 4.2: DAA software to support detecting and responding to cooperative and non-cooperative aircraft and obstacles.
- Recommendation 4.3: Software to support return to mission after a maneuver is completed to avoid a conflict.
- Recommendation 4.4: Procedures and equipage with the technology necessary to ensure safe autoflight to an autonomous landing if there is a loss of communication for command and control by the remote pilot.

  It should be noted that regulations indicating a pathway to approval for DAA based on variants of ACAS-Xr, similar to the recommendations for ACAS II (FAA 2025), are therefore insufficient.

  It should also be noted that the necessary equipage may depend on the procedures associated with a loss of command and control communication (such as declaring an emergency and clearing the airspace).

- Recommendation 4.5: If traffic demand is high enough, an airspace design with unstructured UAM VFR airspace around the charted routes or tracks needs to be considered (see Figure 3) to more effectively allow for deviations around obstacles and diversions.

The remainder of Section 4.0 presents an analysis of the technology paths and associated recommendations for the following functions for Initial Operations Phase 2 (with an emphasis on flights with remote pilots):
- Separation assurance.
- Communications.
- Navigation.
- Vertiports.

Note that the following analysis provides recommendations assuming a destination vertiport that is used by multiple flight operators with a moderate to high level of demand, thereby requiring procedures and technology to support coordination across the flight operators. A traffic manager in the Traffic Management Unit of the ATCT is assumed to be responsible for traffic flow management with input from vertiports and flight operators as necessary. The procedures and supporting automation for the metering of arrivals and for the creation and dissemination of TMIs was previously discussed in Section 2 and apply to Initial Operations Phase 2 with remote pilots. Recommendations for metering and TMIs are therefore not discussed further in this section.

4.1 Initial Operations Phase 2: Separation Assurance

To compensate for the introduction of a remote pilot, DAA technology is required for remotely piloted aircraft in Initial Operations Phase 2. To increase the effectiveness of this technology, eVTOLs controlled by remote pilots are required to have ADS-B In/Out for separation assurance with cooperative aircraft that are similarly equipped. The DAA software must also detect noncooperative aircraft using onboard radar. And DAA validation needs to include full-motion, human-in-the-loop simulations.

The FAA needs to require the following capabilities for aircraft with remote pilots (keeping in mind that some UAM aircraft will have a pilot onboard and therefore will not be required to have equipage for DAA).
- Recommendation 4.6: eVTOLs controlled by remote pilots must have ADS-B In/Out to support separation assurance.
- Recommendation 4.7: eVTOLs controlled by remote pilots must have the capability to maintain well-clear for VFR flight in nominal and off-nominal scenarios.
  - Separation from cooperative and non-cooperative aircraft during departure and arrival.
  - Separation from cooperative and non-cooperative aircraft while enroute and during sequencing and spacing for arrival, including separation and sequencing for landing when a flight is in a holding pattern or has a go-around.
  - Separation when one UAM aircraft overtakes another.
  - Separation when two UAM aircraft have crossing trajectories (see Figure 4). For some airspace designs, this scenario may be precluded by the design of the charted routes.

Potential off-nominal scenarios include area-wide loss of Global Positioning System (GPS)/Global Navigation Satellite System (GNSS) or loss of GPS/GNSS for a single UAM aircraft due to jamming or spoofing or due to GPS/GNSS signal failure. Off-nominal scenarios also include potential loss of separation with a static object and non-cooperative airborne objects:

- Birds.
- Non-cooperative aircraft.
- Weather balloons.
- Other obstacles.

- Recommendation 4.8: Software to support return to mission after an avoidance maneuver. (See Figures 5 and 6).
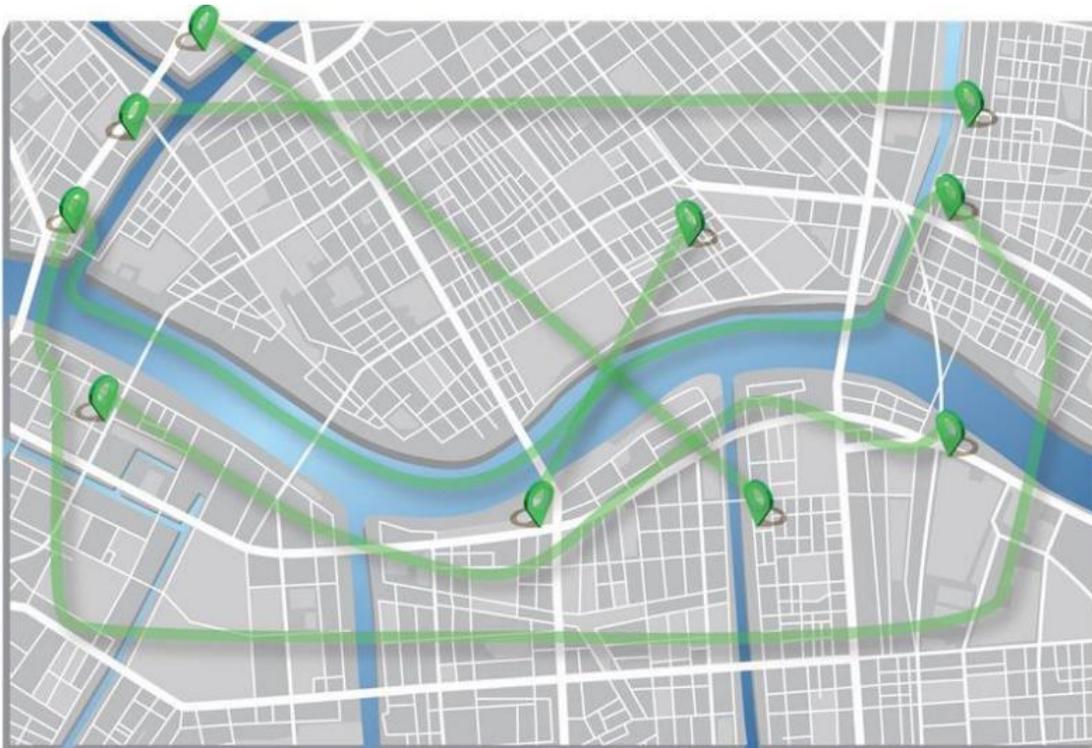
Figure 4. Example of corridors or charted VFR routes (FAA 2023a).

Figure 5. Initiation of an avoidance maneuver (from Honeywell 2024).
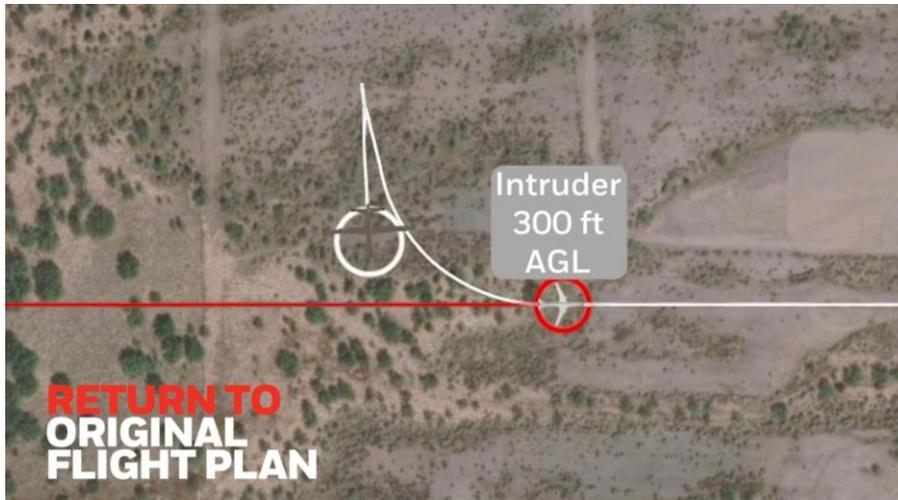
Figure 6. Return to mission (from Honeywell 2024).

4.1.1 Initial Operations Phase 2 - Separation Assurance: Human-Automation Interaction.
ACAS Xr will provide a design that alerts the UAM remote pilot and presents a resolution advisory. The RPIC is then responsible for responding appropriately, given these inputs. Rorie et al. (2023) provide data indicating that it is critical to consider and test the human-automation interaction design for any given DAA system, since the details of the interaction design for such software vary significantly across the designs produced by different manufacturers. Consistent with the approach taken by the Food and Drug Administration to certify medical software, it is necessary to test each design as it would be used, rather than simply testing the software to see if it provides desirable alerts and suggested resolutions.

The need for such testing is indicated by Rorie et al. (2023), who found that "rates of losses of DAA well clear were found to be substantially higher in the Hover scenario compared to Cruise. Pilots failed to fully comply with RAs [Resolution Advisories] at a rate of 0.10-0.18 in all conditions except for the DAA configuration in the Hover scenario, which was associated with a higher non-compliance rate of 0.4 due to Descend RAs issued at low altitudes."

Recommendation 4.9: The FAA needs to develop a requirement for the performance of software supporting DAA and return to mission by remote pilots based on testing of the DAA software using human-in-the-loop evaluations.

4.1.2 Initial Operations Phase 2 - Separation Assurance: Filtering Out Clutter.

A57 (ASSURE 2024) has demonstrated that the onboard radar supporting DAA for non-cooperative aircraft is susceptible to false alarms due to clutter. As a result, it is necessary to introduce filters as part of the DAA to deal with clutter and/or to complement the onboard radar with ground-based radar data transmitted to help filter out clutter. Otherwise, the DAA software can generate invalid alerts recommending a change in trajectory.

To further deal with this challenge with clutter and the precision of DAA software, as noted above, Rorie et al. (2023) suggest that:

"In the terminal environment, the CAS [Collision Avoidance System used in this study] configuration requires the pilot to switch ACAS Xr from the nominal operating mode into a "TA Only" [Traffic Advisory only] operating mode to reduce the likelihood of nuisance RAs. The TA Only mode suppresses RAs [Resolution Advisories] entirely, limiting all alerting to TAs, regardless of the severity of the conflict. This is similar to [Traffic Collision Avoidance System] TCAS II, which automatically switches to TA Only mode below 1000 feet AGL. A manual switch is deemed necessary for ACAS Xr since rotorcraft routinely fly below 1000 feet AGL outside of the terminal environment. Conversely, ACAS Xr's DAA configuration automatically suppresses caution-level alerting and guidance, as well as Horizontal RAs, against intruders in the terminal area. Terminal area intruders are also subject to a smaller DAA well clear volume due to the tight, coordinated spacing around airports. The modifications to the alerting and DAA well clear definition in the DAA configuration are designed to ensure remote pilots are appropriately alerted to genuine conflicts near the airport."

Recommendation 4.10: The FAA needs to determine what is required for separation assurance to ensure safe operations in terms of the design and use of DAA software and airspace design, as well as the contributions of Traffic Manager, ATC, and RPIC performance.

4.2 Initial Operations Phase 2: Loss of Ground Radar

Ground radar systems sometimes fail. Contingency plans need to be defined for such an event.
- Recommendation 4.11: The FAA needs to ensure that procedures for managing airborne flights when the ground radar fails have been defined. This could involve diverting to another vertiport (or ditch site) for which ground radar coverage is available.
- Recommendation 4.12: To the extent possible, the FAA should ensure overlapping coverage for the ground radars supporting individual vertiports.

4.3 Initial Operations Phase 2: Communications

Below, the technology path for communications and associated recommendations are discussed. The emphasis of this analysis is on operations with remote pilots.

Across the full timeframe for the maturation of UAM operations, the parties that potentially need to communicate safety-critical information with each other include:
- Human
  - Pilot on board.
  - RPIC.
  - Operations center staff (dispatcher or flight planner and maintenance).
  - ATC.
  - PSU traffic manager.
  - Vertiport flight manager.
  - Passenger (for emergencies).
- Automation
  - Onboard avionics (including ADS-B, Remote Identification, transponder, DAA).
  - Vertiport automation (including ground-based radar).
  - PSU automation.

o   Flight operations center automation.

Communication can be human-human, human-automation, or automation-automation. The content can include voice communications (analog or digitized), video and other graphics, and a wide range of other digitized information. Figure 7 provides performance recommendations.

Recommendation 4.13: The FAA needs to establish performance recommendations for communications.

	Sub-Category	Direction	Data Rates	Round Trip Time (RTT) (ms)	Reliability – Packet Error Rate (PER)	Priority
C2	Waypoints based (HWTL and HOVTL)	Both	35 kbps	500 [6]	1e-5	Very high
C2	Control of UAM aircraft automation systems in case of HWTL operation	Both	35 kbps	500 [6]	1e-5 and, depending on overall system design, may be up to 1e-9	Very high
C2 Video	For remote piloting	To GCS	4–9 Mbps (720p–1,080p)	500 (same as C2 link)	1e-5 and, depending on overall system design, may be up to 1e-9	Very high
Security System Data (Video/Audio) (Payload)	Safety/security monitoring of the passenger cabin	To a ground monitoring center	4–9 Mbps uplink	500	1e-5 and, depending on overall system design, may be up to 1e-9	Very high
DAA **	Aircraft-to-aircraft For more details, see subsequent section	Broadcast/ Unicast/ Groupcast	35	500	1e-6 up to 1e-7 per DO-377A (link integrity [6])	Very high

Figure 7. Communication performance recommendations based on the RTCA recommendations in RTCA DO-377A (from MITRE 2023). (HWTL=Human Within the Loop; HOTL=Human Over the Loop.)

4.3.1 Initial Operations Phase 2: Recommendations for UAM Aircraft with Remote Pilots Associated with Communications Failures.

There are several areas where support across the range of communication needs requires further advances. These are outlined below.

- Recommendation 4.14: The FAA needs to establish the communications requirements to support remote pilots and autonomous control of UAM aircraft. These recommendations need to:
    o   Identify the full range of communications (content and originators/recipients) that need to be supported.
    o   Identify performance recommendations for architectures to provide seamless transition to backup systems for communications if the primary support for communications is lost.
    o   Define the procedures and required supporting technologies if there is a loss of communication, supporting specific forms of communication.
    o   Standards and supporting communication technology to limit and manage communication delays (command and control and atc-pilot communications)

that are inherent to remote operations. (Existing standards like DO-377B are inadequate.)

Analyses to determine such recommendations can, in part, be guided by RTCA DO-400 (2023), which provides procedures for uncrewed civilian aircraft if their C2 link becomes unavailable or interrupted for an unacceptably long period of time. This RTCA guidance includes consideration of autonomous operations. DO-400 has not been adopted by the FAA yet.

- Recommendation 4.15: Assuming the FAA requires the automation necessary to support autonomous control if one or more remotely piloted aircraft loses communication for C2 by the remote pilot, and assuming the FAA requires an aircraft with a remote pilot that loses communication for C2 to autonomously fly its current planned trajectory to its destination, there are several implications:
    - Before departure, the automation must know the full 4D trajectory, including the planned approach path and landing pad. The automation must be updated with any amendment made to this 4D trajectory while the flight is enroute (which is also known by the RPIC). This applies even if the flight is flying along a UAM VFR corridor, as it needs to be prepared to transition to autonomous flight if necessary.
    - The onboard software must be able to determine when communication has been lost for some period of time and then switch to autonomous flight.
    - The software must have autonomy capable of:
        o Autonomous auto-flight prior to reaching the destination vertiport or pre-planned alternate.
        o Autonomous DAA to ensure the aircraft is "well clear" of other aircraft and objects and responds appropriately for collision avoidance.
        o Autonomous "return to mission" if a DAA resolution moves the flight off its planned trajectory (see Figures 5 and 6).
            ▪ The software not only needs to compute the trajectory to implement a collision avoidance maneuver, but it also needs to compute the trajectory to "return to mission" after this maneuver is completed.
            ▪ It should be noted that both this autonomous DAA maneuver and the return to mission should take into account airspace procedures and constraints, including the approach path to land at the destination vertiport. An example would be UAM flights flying to a vertiport located in the middle of LAX that need to fly a trajectory that does not conflict with the departure SIDs and arrival STARs used by the aircraft operating on the runways at LAX.
            ▪ The software also needs to determine whether the flight has a sufficient power supply to fly the computed 4D trajectory and have a contingency plan to deal with a scenario where the power supply is not adequate to land and the planned destination vertiport. If, to reduce the required reserve energy supply to 20 minutes, the flight planner has included a ditch site along the route of flight, the contingency plan could involve diverting to that ditch site.
            ▪ Autonomous precision auto-land. Note that it also could be desirable for the aircraft to loiter for some short time period at some

> predefined point on its 4D trajectory to enable clearing of the airspace of other flights as necessary and to ensure that the vertiport landing pad is clear.
> - Certain other procedures also need to be defined when communication is lost. This includes a requirement that the remote pilot inform the vertiport, and, as appropriate, inform ATC that the aircraft has lost communication. Having received such a notification, an emergency would need to be declared and communicated to all relevant parties (ATC, vertiport staff, and all UAM aircraft with onboard or remote pilots in the area).

In addition, it is likely that arrival and departure stops at the destination vertiport would also have to be declared and disseminated by the appropriate authority in the case of a loss of communications for C2. UAM flights that still have communication for C2 and that are already airborne with that vertiport as their destination would have to be managed appropriately, along with managing all of the other air traffic in the area.

In terms of a gap, DAA systems based only on ACAS-Xr do not have this full range of capabilities. The onboard avionics need to be able to translate a DAA Resolution Advisory into a trajectory that assures separation while still enroute, returns the flight to its mission (see Figure 6), and controls a precision landing that manages separation and sequencing for aircraft in vertiport airspace.

This suggests a number of corollary recommendations to maximize safety by providing all relevant parties with the preflight flight plan and any updates representing the last received and acknowledged route clearances on the assumption that the automation has been programmed to fly the last received and acknowledged route clearance if comms are lost.

- Recommendation 4.16: When a UAM aircraft is filed to fly a VFR route, the flight plan should be disseminated and updated as if it were flying Instrument Flight Rules (IFR) so that the planned route (updated with any amendments while enroute) is known to all parties if there is an LC2L (Loss of Command and Control Link) event.
- Recommendation 4.17: Before departure, the automation must know the full 4D trajectory, including the planned approach path and landing pad. The automation must be updated with any amendment made to this 4D trajectory while the flight is enroute (which is also known by the RPIC).
- Recommendation 4.18: The onboard software must be able to determine when communication has been lost for some period of time and then switch to autonomous flight.

Caution: Without coordination, individual urban centers could proceed to develop local solutions to address these questions. If there isn't some centralized guidance or a set of recommendations from the FAA, this could result in a system that is difficult to manage in terms of future updates on software and procedures.

- Recommendation 4.19: Detailed analyses are necessary to determine the reliability of the primary and backup communications systems. The FAA needs to establish performance

requirements relative to capacity, latency, reliability, and security. Examples of scenarios where a LC2L event could occur that merit consideration are:

- o Hardware or software failures.
- o Direct attacks on the communications infrastructure itself.
- o Emergency evacuation of a flight operations center, leaving all of its flights unattended.
- o Spoofing of GPS impacting C2 systems that rely on GPS for encryption.

This could also include an indirect attack on those C2 systems that make use of GPS to support encryption. This concern is encompassed by the Presidential Memorandum on Space Policy, Directive 7 (Presidential Memo, 2021):

"The widespread and growing dependence on GPS by military, civil, and commercial applications, systems, and infrastructure make the performance of many of these systems inherently vulnerable if disruption or manipulation of GPS signals were to occur. GPS users must plan for potential signal loss and take reasonable steps to verify or authenticate the integrity of the received GPS data and ranging signal, especially in applications where even small degradations can result in loss of life. In addition, whether designed for military capabilities or not, signals from PNT services and their augmentations provide inherent capabilities that may be used by adversaries, including enemy military forces and terrorist groups."

More specifically, concerning GPS and potential overreliance on GPS in safety-critical systems (Reuters 2024), there are potential risks related to position as well as the use of GPS as a time source. Time sources are often used for encryption. Hence, if GPS is spoofed and used as a time source without mitigations for spoofing, it may result in a loss of encryption capability and, hence, a loss in communication and C2.

This concern is not just a theoretical possibility; there are numerous incidents where GPS systems used for aviation have been spammed and spoofed (SAFO 2024), including an event in commercial aviation where GPS time was hacked, which then impacted encryption. In this type of event, multiple UAM aircraft could lose C2 at the same time.

For a significant duration into the future, Very High Frequency (VHF) communications with ATC will have to be supported. As Stouffer et al. (2021) note: "Any conversion of the ATM conversations to digital-only communications would require FAA ATC equipage." However, the potential for hundreds of UAM vehicles to operate under Class B/C/D airspace indicates the need for a solution to reduce this communication overload.

- Recommendation 4.20: Develop requirements for the equipage necessary for conversion of the ATM conversations to digital-only communications with ATC.

Numerous variations are being explored regarding some of the network solutions (Erturk et al., 2020; Stouffer, Cotton, et al., 2021; Zaid et al., 2023).

- Recommendation 4.21: Integration of Artificial Intelligence: There are proposals to apply Artificial Intelligence (AI) to standalone 5G technology for UAM control systems and aerial communications networks (Jeong 2023). This introduces unique challenges in terms of the evaluation of such systems for reliability. FAA guidance on this needs to be provided.

4.4 Vertiport Technology and Associated Gaps

In this section, the technology path is discussed for the design and use of vertiports for Initial Operations Phase 2. Associated needs are also discussed. This analysis focuses on the use of remote pilots to control departures, landings, missed approaches, and holding at vertiports. Figure 8 shows a notional example of a vertiport design. In this analysis, a moderate or high level of demand is assumed so that simple RPIC to RPIC coordination for arrival and landing is not sufficient, making a vertiport flight manager necessary.

To manage departures, roles and responsibilities depend upon the airspace classification of the arrival and departure vertiports. As an example:
- For departures into Class B/C/D airspace, ATC provides the clearance to depart based on an assigned release time.
- For arrivals in Class B/C/D airspace, ATC provides the clearance to land.
- It is not clear to what extent, if any, vertiport flight managers in Class G airspace will play a role in clearances for departure and landing.
- For arrivals at an airport in Class B/C/D airspace, ATC determines the vertiport arrival rate(s).
- For arrivals at a vertiport in Class G airspace, the process for determining vertiport arrival rate(s) needs to be determined.
- For arrivals at an airport in Class B/C/D airspace, ATC is responsible for traffic flow restrictions affecting vertiport arrival rate(s) with input from the vertiport, FOC, PSU, and flight operators, which is then used by automation to assign release times. As noted earlier, the shared responsibility for the implementation and use of such automation needs to be determined.
- It is not clear who, if anyone, is responsible for traffic flow restrictions associated with vertiports that are not in ATC-controlled airspace. In some of the following discussions, it is assumed that a vertiport flight manager has this responsibility (assuming traffic levels are high enough to require traffic flow restrictions).

Figure 8. Notional example of a vertiport (from Eve 2023).

- Recommendation 4.22: FAA recommendations are needed specifying performance recommendations for the automation necessary for the vertiport flight manager to:
    - Support the use of reservations and ground delay programs with a strategy to accommodate different business models (regularly scheduled flights vs. pop-ups), including support for swapping arrival slots within and across flight operators. It is not clear who will be responsible for the reservation system (the FAA vs. each vertiport vs. a PSU).
    - Provide input regarding vertiport capacity to the ATCT Traffic Manager for setting arrival rates and initiating Traffic Flow Restrictions (TFRs), including decisions to initiate departure and arrival ground stops.

As noted in earlier recommendations:
- It is assumed that an FAA Traffic Manager in the ATCT will set arrival rates for vertiports in ATC-controlled airspace, which software will translate first into a set of available arrival slots and then into a set of release times.
- For vertiports in airspace that is not controlled by ATC, a determination is needed as to who will specify arrival rates for that vertiport.
- A reservation system will be used to assign individual flights to these arrival slots, but a decision is needed regarding who will be responsible for this reservation process and the supporting software.

As an example of progress in developing vertiport software, ANRA (2023) has developed vertiport management software to allow UAM operators to plan and execute their flight operations from pad to pad, supported by a comprehensive suite of services, including:
- Real-time vertiport resource status and reservation requests.
- Resource schedule for vertiport resource availability.
- Reservation and clearance requests for inbound and outbound flights.
- System checks to verify the status of outbound flights.
- Live telemetry for monitoring aircraft data of inbound and outbound flights.
- Micro weather services.
- Live surveillance data for nearby aircraft.
- Integration with broader UAM traffic management systems.

An FAA standard has been developed that applies to the design of approach and departure paths for vertiports:
- Recommendation 4.23: In terms of recommendations for the design of vertiport airspace, the existing FAA standard (FAA 2022a) for vertiport airspace design (FAA 2022b) applies to vertiports serving UAM aircraft with onboard pilots and UAM aircraft that are remotely piloted. This FAA standard provides specifications for the design of the approach and departure paths for vertiports, defining the "flight track that VTOL aircraft follow when landing at or taking off from a vertiport" (see Figure 9).
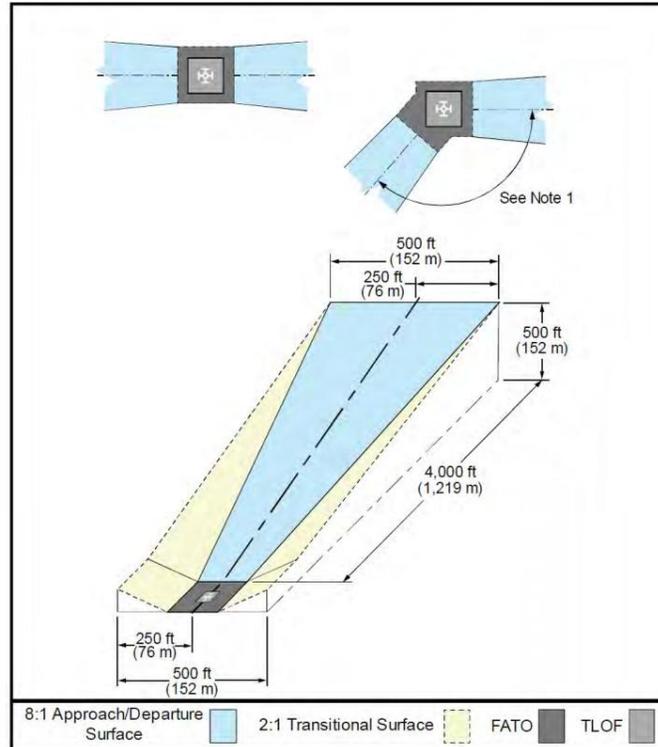
Note 1: The preferred approach/departure surface is based on the predominant wind direction. Where a reciprocal approach/departure surface is not possible in the opposite direction, use a minimum 135-degree angle between the two surfaces.

Figure 9. Approach airspace for vertiport (from FAA 2022b). (FATO= Final Approach and Takeoff Area; TLOF=Touchdown and Liftoff Area.)

Figure 10 provides one concept for the placement of such approach/departure paths.

Fig. 1. eVTOL arrivals at a vertiport - concept of operations.
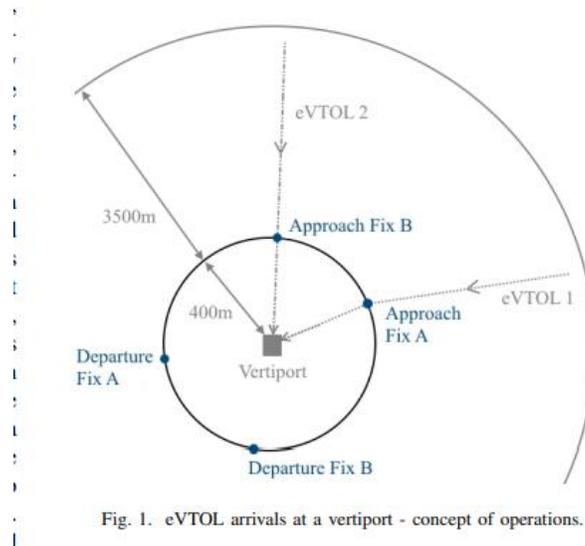
Figure 10. Arrival and departure fixes for a vertiport (from Kleinbekman et al. 2018).

4.4.1 Coordination of RPIC with Vertiports.

Even if traffic demand is light, the flight planner or RPIC should receive approval indicating that the planned use of the arrival vertiport airspace and a landing pad will be available upon arrival.

This could take the form of an assignment of a release time for departure for a specific flight based on regularly updated information about the arrival slots and landing pads.

- Recommendation 4.24: The ground control station for the remote pilot and/or flight planner needs to support coordination for pre-departure planning. For the RPIC and flight planner, this includes information displays indicating:
    - Status of the planned vertiport destination and alternate vertiports (including status of landing pads, parking spots, associated TFRs, and NOTAMS).
    - Projected traffic demand relevant to departures and arrivals at vertiports.
    - Scheduled release times for aircraft departures and any revision of these release times closer to wheels up (OFF).
    - Current and forecast winds, convective weather, and winter weather conditions, as well as other constraints in the vicinity of the departure or arrival vertiport. (Should the vertiport provide real-time, on-site automated weather data, such as Automated Weather Observing Systems (AWOS), to all UAM?)
    - Flight planning software to support the generation of flight plans (including contingency plans) using the information listed above. Note that this flight planning software needs to determine energy supply Recommendations, including the FAA-required reserves and a sufficient energy supply to divert to planned alternate landing sites. (This will be addressed in more detail in the section on preflight planning.)
- Recommendation 4.25: The ground control station for the vertiport flight manager needs to support coordination (through software) with the party responsible for setting arrival rates and translating these rates into reservations with associated arrival and departure slots. Either ATC, the PSU, or the vertiport could provide this information to flight planners and RPIC (something that needs to be determined). The flight planners or RPICs would, in turn, be providing these parties with information regarding their proposed flight plans that meet the constraint of the assigned release time for a flight.

    Note that the flight plan could include diversion to some vertiport(s) or ditch sites as a contingency, so the flight planner and RPIC could be providing information regarding multiple vertiports.
- Recommendation 4.26: The report for Task 2 of this project indicates that, if demand is high relative to vertiport capacity, there is a need for pre-flight and real-time coordination if multiple aircraft need to divert from a specific vertiport (due to weather or some other constraint that closes or limits the capacity of one or more vertiports). Software to support this may become necessary if traffic demand is sufficiently high. The process and responsibility for evaluating alternate and approving landing sites, including assignment of the responsibility to complete this process, needs to be determined.
- Recommendation 4.27: For vertiports in ATC-controlled airspace, approvals for proposed departure times will be centralized through an ATCT traffic manager supported by software. Again, the assignment of this responsibility for vertiports that are not in ATC-controlled airspace needs to be determined. Approvals need to be communicated to flight planners and RPICs through software.

4.4.2 Initial Operations Phase 2: All Clear for a Landing Pad.

The procedure for clearing a UAM flight to land may vary depending upon whether or not the vertiport is situated within ATC-controlled airspace. If so, ATC provides the clearance to land.

If not, and volume is moderate to high, it needs to be determined whether or not a vertiport flight manager provides the clearance, potentially supported by automation that provides a safety net to help monitor that a landing pad is available.

As noted earlier, for low-volume private vertiports or departure pads in Class E or Class G airspace, current procedures for helicopter operations apply, relying on communication and coordination among the arriving and departing UAM aircraft via CTAF/UNICOM.

- Recommendation 4.28: Requirements for automation to help ensure landing pads are clear for safe landings need to be developed, potentially including the use of downward-facing cameras on the aircraft (McNab 2023).

4.4.3 Additional Capabilities of a Vertiport Ground Station.

As indicated earlier, if traffic demand is sufficient to preclude simple RPIC to RPIC coordination as flights converge to land at a vertiport and the vertiport is not in ATC-controlled airspace, a vertiport flight manager may be required. Below is a summary of the responsibilities of such a person and the automation necessary to support the fulfillment of these duties.

- Recommendation 4.29: A decision needs to be made regarding the requirements for a vertiport ground station to support the vertiport flight manager.
  - The vertiport flight manager needs access to weather information.
  - The vertiport flight manager needs to have the ability to coordinate with the FAA traffic manager (or some other appropriate authority for vertiports that are not in ATC-controlled airspace) to provide information relevant to determining arrival capacity or to request a vertiport departure or arrival stop. Software supporting the creation of such restrictions needs to be provided. Thus, the following questions regarding the creation and dissemination of traffic flow restrictions need to be addressed:
    - Who has the responsibility and authority to create and disseminate traffic flow restrictions indicating vertiport status? (depending upon whether or not the vertiport is in ATC-controlled airspace)
    - Who should provide input to this decision-making?
    - How will traffic flow restrictions be created and disseminated?
    - What expertise in meteorology and traffic flow management is required for decisions regarding vertiport status?
    - Who has the responsibility and authority to clear a flight for departure? (depending upon whether or not the vertiport is in ATC-controlled airspace)
      - ATC if in ATC-controlled airspace vs. vertiport flight manager? What displays and automation are necessary to support this?
    - Who has the responsibility and authority to manage sequencing and spacing and clear a flight for landing (depending upon whether or not the vertiport

is in ATC-controlled airspace)? What displays and automation are necessary to support this?

- ATC if in ATC-controlled airspace?
  - Who has the responsibility and authority to manage missed approaches (depending upon whether or not the vertiport is in ATC-controlled airspace)? What displays and automation are necessary to support this?
    - ATC if in ATC-controlled airspace?
    - Vertiport flight manager?
    - RPIC or PIC?

As noted above and in the report of Task 2 of this project, a process and supporting vertiport management automation needs to be provided to manage scenarios where multiple flights need to divert.

4.5 Initial Operations Phase 2: Aircraft Management for RPICs

The RPIC manages the flight while enroute with flight following by ATC if the aircraft is in ATC-controlled airspace, taking advantage of autoflight and autoland capabilities to complement any manual flying of the aircraft by exception:

"A significant component of UAM is offloading of flight-management responsibilities from human pilots to newly-developed autonomy" (NASA 2023).

Figure 11 shows an example of the pilot interface for an eVTOL with a pilot onboard.
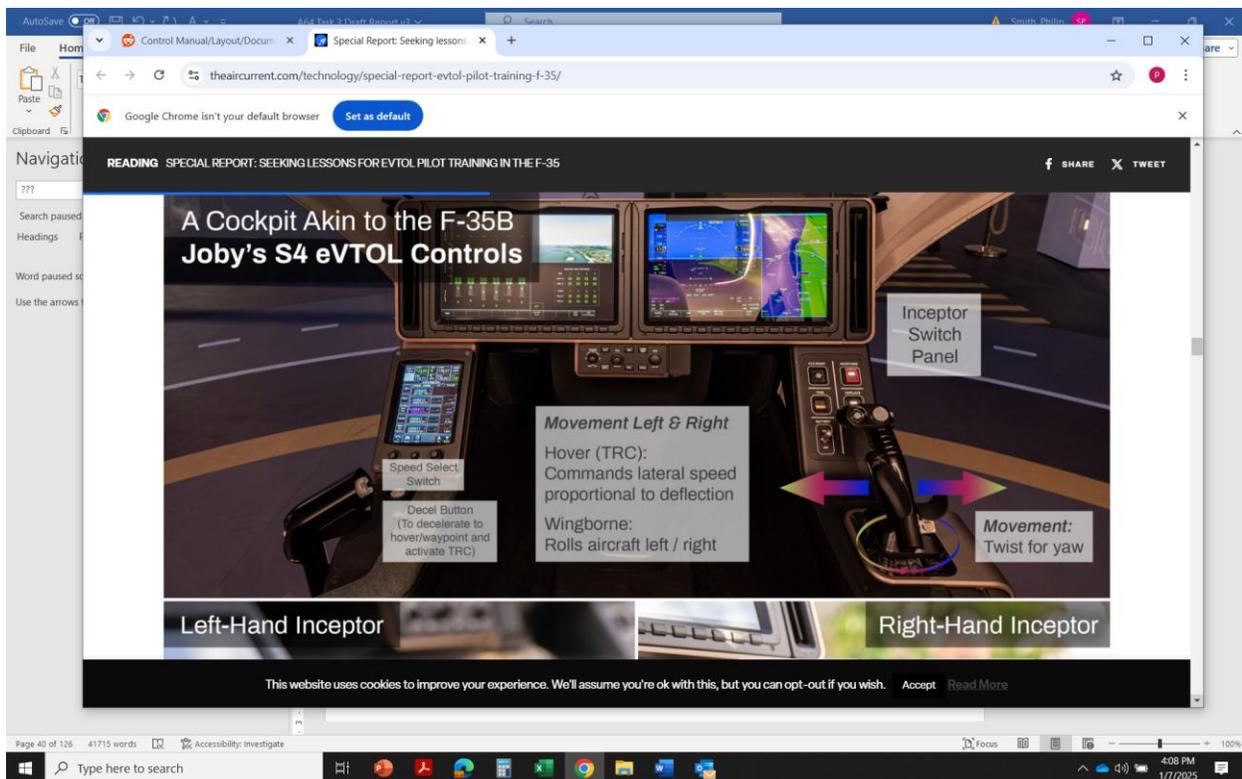
Figure 11. Sample eVTOL interface for an onboard pilot (from Head 2024).

- Recommendation 4.30: The interface designs to support remote pilots are expected to differ for each of the eVTOLs under development. As part of the certification process for aircraft flown by remote pilots, performance by RPICs using these interfaces needs to be evaluated for the full range of nominal and off-nominal scenarios.

Feary et al. (2023), for example, suggest:

> "Adaptation of an evaluation design standard used by the military for advanced rotorcraft along with proposed descriptions and definitions to support evaluation of diverse automated concepts in the civilian eVTOL community."

5.0 TECHNOLOGY DEVELOPMENT: MIDTERM OPERATIONS

One primary feature defining the transition to Midterm UAM Operations is the introduction of structured airspace to support heavy traffic demand. A second feature for Midterm Operations is much more comprehensive preflight deconfliction. The latter requires considerable additional research regarding roles and responsibilities, as well as the software architecture to support the necessary decisions.

The discussion below focuses on strategic deconfliction for flights arriving at and departing from airports in Class B/C/D airspace where ATC will control departures and arrivals. Consistent with FAA conclusions based on a detailed study of UAM operations for LAX, it is assumed that the setting of arrival rates for metering arrivals and the creation of TMIs will be the responsibility of the ATCT Traffic Manager. These decisions must then be translated into the assignment of arrival slots to individual flights, which must then be translated into the assignment of departure release times. A process mimicking TBFM is then assumed to be applied to revise assigned release times shortly before OFF to reflect the actual flow of traffic.

As indicated earlier, decisions about who will have responsibility for the translations resulting in the final release time for a flight need to be determined. This then raises questions about how to integrate decisions based on strategic deconfliction, as discussed below with the dynamic decisions made regarding the final OFF times for flights. **It should be noted that this question regarding integration does not seem to be addressed in the literature.**

Because in Midterm Operations demand is assumed to be high relative to capacity, the proposed 4D trajectory for each flight must be approved by some party with automation support. This automation will automatically evaluate and respond to a flight plan request with the traffic manager managing by exception.

To highlight necessary automation support, the discussion below assumes that a PSU traffic manager will be given this responsibility for traffic flow management. However, important decisions will have to be made relative to the distribution of roles of responsibility, as the role of the ATCT Traffic Manager needs to be considered. Furthermore, it is not clear whether PSUs will be willing to take on this role and whether the FAA is willing to let PSUs take on this role.

5.1 Midterm Operations: Assumptions

There are contrasting views regarding the airspace for UAM usage. One approach is for much more integration rather than segregation of UAM operations as the regulatory hurdles to create exclusive use airspace for UAM would be tremendous. However, there has been substantial research and discussion regarding the design and use of segregated airspace as well.

There are several assumptions regarding Midterm Operations:
- There is high demand relative to the capacity of the airspace and vertiports.
- If a segregated airspace design is considered, except when off-nominal conditions require otherwise, planned operations for UAM flights are restricted to predefined corridors that have separate directional routes with passing lanes:
    - Corridor design will segregate flights based on their direction through a corridor (via altitude or lateral separation).
    - Passing lanes will be incorporated to deal with flights flying at different speeds.
    - As with Initial Operations Phase 2, holding patterns around vertiports or in enroute airspace will provide a structured method to delay landing when necessary.
    - Vectoring or routing outside of UAM corridors is possible but is by exception.
    - Vertiports have defined SIDs and STARs associated with the corridors associated with different vertiport configurations.
    - Many UAM aircraft are remotely piloted, but others have a pilot on board.
    - There is a single remote pilot per UAS.
    - As with Initial Operations Phase 2 discussed above, all aircraft are equipped to fly autonomously if communications are lost.
    - Each UAM aircraft has a well-specified Required Navigational Performance (RNP). Note that the design of corridors needs to enable safe navigation, given the minimum required RNP for aircraft.
    - UAM aircraft with remote pilots have DAA capabilities.
    - Contingency plans need to consider the potential impact of possible "environmental" factors or other off-nominal events while enroute. This includes factors such as weather that could require rerouting an aircraft along a new 4D trajectory to its destination or a diversion landing site, or that could require temporary vectoring off the planned flight path (out of the planned corridor). Although unexpected weather constraints should arise infrequently, given the short duration of most UAM flights, it has to be assumed that weather or other constraints will sometimes arise. These contingency plans include alternate landing sites when appropriate.
    - With automation support, the responsible PSU traffic manager must provide preflight approval of deconflicted 4D trajectories based on knowledge of DAA capabilities, rules of the road, TFRs, NOTAMS, weather, other already approved 4D trajectories (for flights with already approved preflight flight plans or other airborne flights), vertiport status and contingency plans for UAM flights seeking to fly or already airborne. This deconfliction process needs to somehow be integrated with the dynamic process for updating release times using a TBFM-like procedure as described earlier.

- As discussed in the A64 Task 2 report, this approval of contingency plans considers deconfliction of planned alternate vertiports and landing sites, not just the planned 4D trajectory while enroute.
- RPICs with supporting DAA are responsible for and have the authority to make tactical adjustments to maintain separation while flights are airborne.

5.2 Midterm Operations: Airspace Usage and Route Structure

The major new step assumed for Midterm Operations focuses on assumptions about airspace design. First, for nominal operations, it is assumed that, when possible, the 3D trajectories approved for flights route them through pre-defined UAM enroute corridors that are restricted to some altitude range to be defined somewhere between 400-4000 ft. Most of the CONOPs suggest something in the range of 1000-1500 to 4000 ft. NASA (2024) suggests that these corridors as "3,000 ft width, tracks that are 1,500 ft apart." Figure 12 provides dimensions for approach and departure airspace to and from vertiports.

There are separate corridors containing one-way routes for flights in different directions with passing lanes (see Figures 13-14). These corridors are embedded in UAM VFR enroute airspace (as indicated by the yellow regions in Figure 3). And there could be multiple parallel tracks within each corridor. Outside of the corridors, this airspace is not used for planned 4D trajectories, but rather is available to support necessary routing and vectoring to support off-nominal UAM operations such as vectoring and diversions.

As discussed earlier, flights that need to vector around convective weather can do so by vectoring or rerouting into this additionally defined unstructured UAM airspace. Flights that need to divert to a different destination (vertiport or emergency landing site) can also transit this unstructured UAM airspace (see Figure 3).

It should be noted that there are a variety of other proposals for airspace design (Bauranov & Rakas, 2021). The description above, however, serves to highlight the important safety automation considerations.
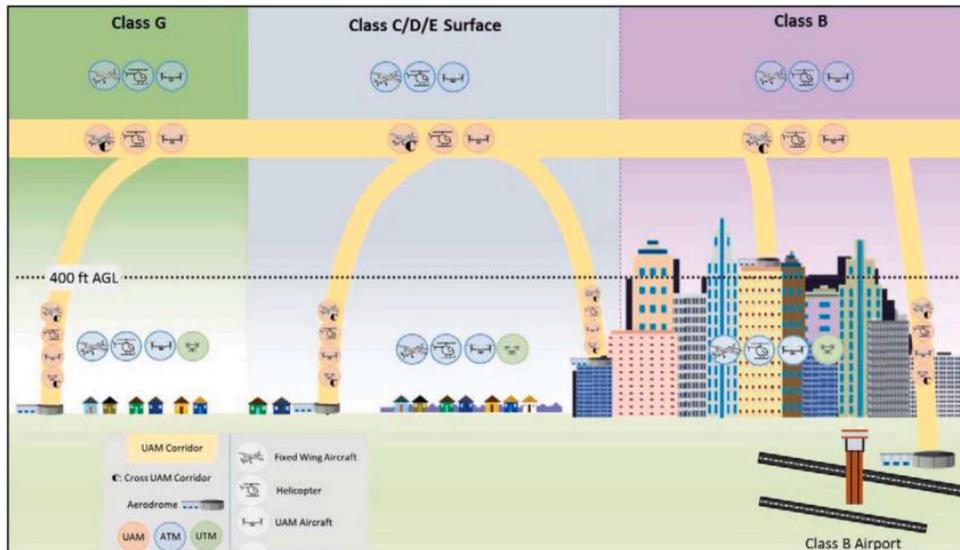
Figure 12. UAM Corridors (from Bauranov & Rakas, 2021).
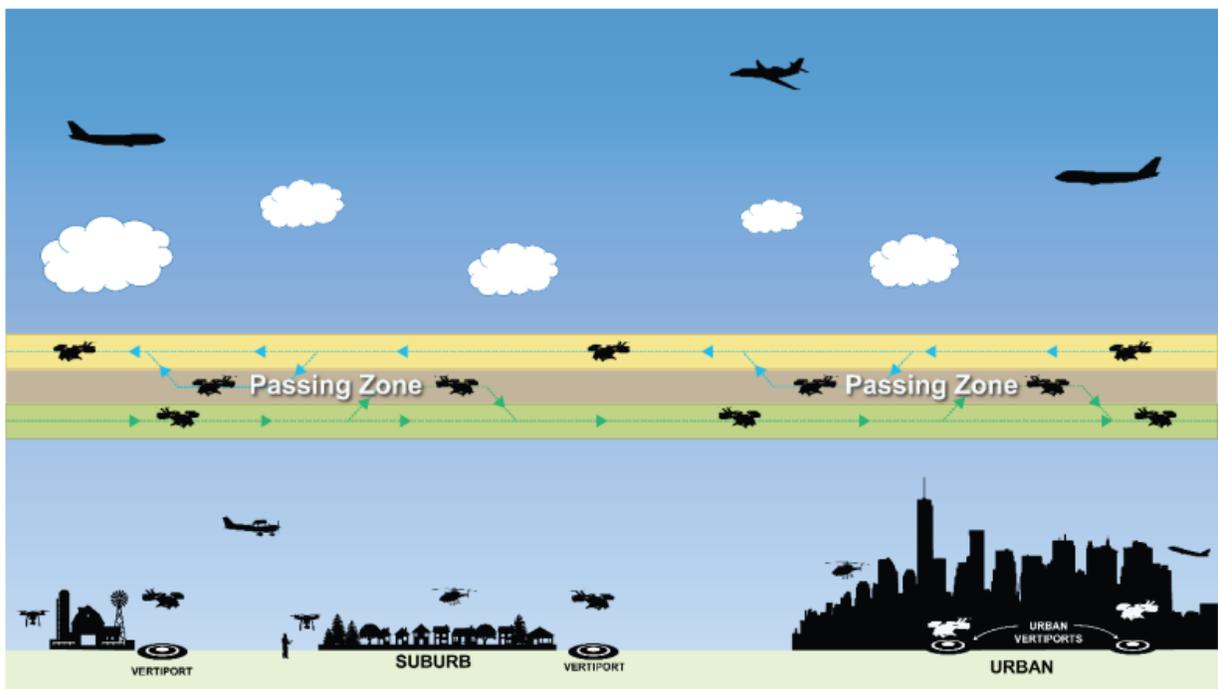
Figure 13. One-way corridors with vertical common passing zones - side view (from FAA 2023).
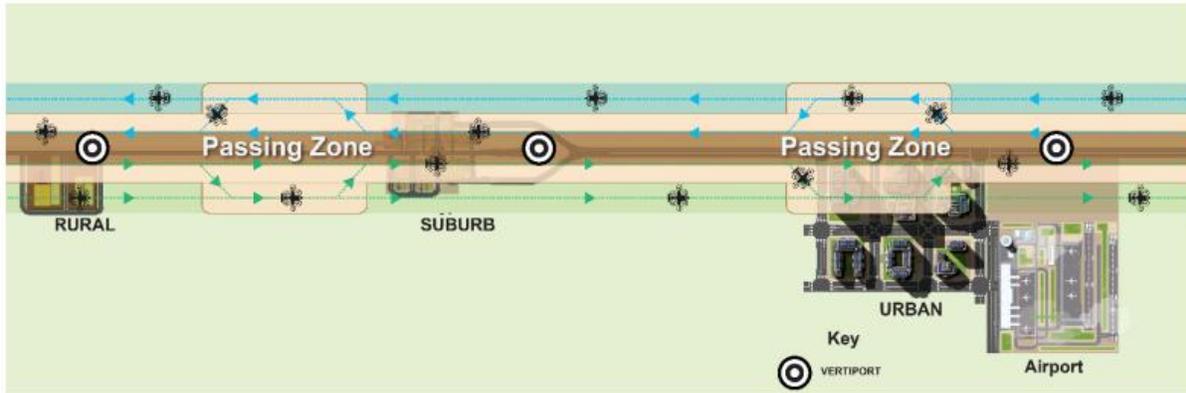
Figure 14. One-way corridors with lateral common passing zones – top-down view (from FAA 2023).

Another dimension of airspace design is the development of designs and procedures for holding patterns in the vicinity of vertiports. As Figure 15 illustrates, there are a variety of proposals that need to be considered and evaluated.
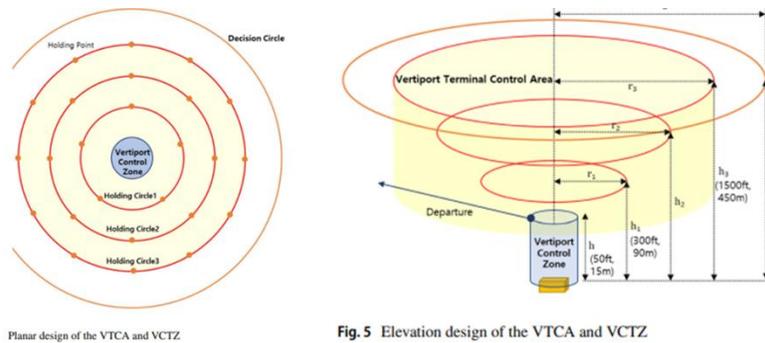
Figure 15. Examples of a design for vertiport holding patterns (from Song 2023). (VTCA= Vertiport Terminal Control Area; VCTZ=Vertiport Control Zone.)

5.3 Midterm Operations: Preflight Planning and Preflight Strategic Deconfliction

Since the primary innovation for Midterm Operations is to introduce structure to safely accommodate a level of traffic demand that is high relative to capacity, it is important to understand the process that needs to be supported. The relevant tasks are noted below.

5.3.1 Preflight Task: Creation and Dissemination of TFRs.

An earlier section discussed the considerations surrounding metering of arrivals and the creation and dissemination of TMIs. The structured airspace introduced for Midterm Operations and the need for strategic deconfliction of planned 4D trajectories extend the scope that needs to be considered for these considerations. For example, an FAA Traffic Manager will need to consider TMIs for enroute airspace, not just TMIs affecting arrival rates.

5.3.2 Flight Plan Deconfliction.

Although details still need to be determined, assume that at 45 minutes before the desired OFF, the flight planner prepares and submits a proposal for the operational intent for a departing flight to the PSU traffic manager. (Note: For smaller operations, this could be performed by an individual

PIC or RPIC.) This proposal includes a prioritized list of alternative 4D trajectories, each with an associated acceptable range for the Estimated Time of Arrival (ETA) to the destination vertiport. It also contains a contingency plan with alternate landing sites to accommodate changes in destination (alternative vertiports, ditch sites, and emergency landing sites) due to off-nominal events. Note that a different contingency plan could be associated with each proposed 4D trajectory.

- Subtasks
  - o To request approval for a flight plan, the flight planner or RPIC (with software support):
    - Prepares a proposed operational intent (flight release) for an upcoming flight by:
      - Consulting with the meteorology expert.
      - Reviewing -
        - Schedule for upcoming departure and connecting flights for that flight operator.
        - Current and forecast UAM traffic display for corridors and vertiports.
        - Current and forecast traffic in ATC-controlled airspace.
        - Current and forecast weather.
        - TFRs and NOTAMS for relevant vertiports.
        - Vertiport status (availability and Minimum Equipment Lists
          - o Status of possible alternative vertiports (for diversion).
      - Determining -
        - Availability of ground crew for departure.
        - Availability of the aircraft.
        - Availability of departure pad.
      - Determining the suitability of an operational intent given -
        - Aircraft capabilities/performance specifications (e.g., RNP, DAA capabilities, energy recommendations including reserve fuel, flight restrictions such as winds, etc.).
      - Coordinating aircraft or crew changes as necessary.
      - Preparing the operational intent message with support from flight planning software to ensure a complete and viable proposal. This proposed flight plan could indicate an earliest time of departure or a range for the ETA that is acceptable. Note that this proposal, to be submitted to the PSU strategic deconfliction software for approval, contains a prioritized list of alternative routes. Note also that this proposal needs to include a contingency plan indicating the required fuel.
      - Submitting the proposed operational intent (including contingency plan) to the PSU strategic deconfliction software.
        - To approve the proposed operational intent for a flight, the PSU strategic deconfliction software evaluates the request, including availability of an arrival slot, landing pad, parking

spot, and proposed alternates, with the PSU traffic manager monitoring and intervening by exception based on:

- Traffic flow restrictions.
- Other potentially conflicting already approved 4D trajectories (enroute and preflight).
- Availability of landing pad and parking pad.
- Capacity of alternate landing sites in case diversions are required for multiple aircraft (see detailed description in Task 2 report).

- The flight planner submits a revised operational intent (alternative 4D trajectory and contingency plan) to the traffic management system if the initial submission is rejected.
- Upon approval of the flight plan and contingency plan, the flight planner finalizes the flight release with the approved 4D trajectory and ETA and submits it to the onboard pilot or RPIC. Based on the approved ETA, the Estimated Time of Departure is calculated and included in this flight release.
- The PIC or RPIC approves the flight plan.
- The flight plan (including contingencies) is submitted. As noted earlier, if this flight plan traverses ATC airspace, then it needs to be submitted to ATC as well. A format for this flight plan needs to be defined that ATC software can accept.
  - Preflight Task- Flight Plan Deconfliction: Recommendations
    - Recommendation 5.1 Procedures and software need to be developed to support:
      - Software for the development and dissemination of TFRs and NOTAMs by the ATCT Traffic Manager. This includes receipt of input from vertiports, ATC, and a meteorologist.
      - Software to support flight planner preflight development and submission of flight plans for approval. Note that there have been proposals to centralize flight planning by the PSU. A decision regarding this alternative needs to be made.
      - Software to support PSU traffic manager evaluation of a proposed flight plan for deconfliction (completed automatically by default using PSU flight deconfliction software with management by exception by the PSU traffic).
      - Software to support coordination among multiple PSUs is there are several.

5.3.3 Enroute Deconfliction.

The onboard or remote pilot views a display provided by the enhanced Visual Flight Rule software as described earlier to tactically resolve enroute conflicts routinely before the DAA software triggers an alert regarding the potential for a well clear violation.

- Recommendation 5.2: An advanced version of the enhanced Visual Flight Rule software is needed that applies knowledge of the airspace structure, as well as defined vertiport holding patterns and procedures for go-arounds to provide effective situation awareness to the RPIC.
- Recommendation 5.3: The DAA software needs to apply knowledge of the airspace structure, as well as defined vertiport and enroute holding patterns and procedures for go-arounds to provide effective situation awareness and alerts to the RPIC. Consistent with

the philosophy of ACAS, the RPIC is alerted and initiates a recommended conflict resolution. A specification of an advanced version of ACAS Xr that considers the structure of the airspace is required to provide this. An open question is whether and when the DAA automation should autonomously initiate a conflict avoidance maneuver.

- Recommendation 5.4: If the RPIC chooses to use the passing lane, an alerting function warns of a potential conflict before a passing maneuver is initiated (see Figures 13 and 14).
- Recommendation 5.5: If communication for C2 is lost as discussed in Section 4.0, the software to initiate and control autonomous flight requires knowledge of the airspace structure (see Figures 12-14) and the planned current 4D trajectories for the other flights in the airspace. When an RPIC amends a route through the autoflight function, this route should be communicated to the PSU, vertiport flight manager, and ATCT controller at the AAM position.

Note: The DAA software must also deal with the case where another flight has made a maneuver off of its planned 4D trajectory using manual control such that its current 4D trajectory is unknown.

6.0 TECHNOLOGY DEVELOPMENT: MATURE UAM OPERATIONS

Mature operations introduce a greater degree of autonomy (Honeywell 2022) for some (but not necessarily all) UAM aircraft. Since complete autonomy for flights with remote pilots (including autonomous triggering of the software responsible for DAA and return to mission) is expected to be required by the FAA for response to lost communication for command and control as early as Initial Operations Phase 2 (with remote pilots), this capability will have been exercised well before Mature Operations. There are standards such as IEEE PS7009 (2024) to help guide the development and evaluation of such software:

> "This standard defines capabilities to assist operational autonomous and semi-autonomous systems preserve freedom from unacceptable risk of harm. When realized as an integral element of an operational Safety Management System, the capabilities documented in this standard provide a basis for interventions to assist management of safety in the event that systems operating either autonomously or semi-autonomously exhibit anomalous behavior."

The major change for Mature Operations is the introduction of multi-aircraft supervisors (NASA m:N 2024) who each manage multiple aircraft in an environment with high demand, keeping in mind that there likely will also be flights with onboard pilots and flights where the RPIC remotely controls a single aircraft. These aircraft will fly autonomously, controlled by exception if something arises that requires intervention by the multi-aircraft supervisor. It should be noted that this is not simply a software challenge; it is also a staffing and organizational design challenge to ensure attentive supervisors who have backup personnel to assist when significant off-nominal scenarios arise.

A second possible change would be the ability of the same party (the ATCT Traffic Manager or PSU traffic manager) to dynamically introduce new corridors to structure traffic around some known or predicted constraint, such as weather (MITRE 2019).

The CONOPs for multi-aircraft supervisors is described in Boeing/Wisk (2023):

"This ConOps presents the use of system designs that enable M:N concepts (e.g., [Multi-Vehicle Supervisor] stations and UAM aircraft). However, as previously stated, the ratio of supervisor-to aircraft may vary based on the operator's operational specifications, capabilities, aircraft automation, standard practices, and agreements with ATC. All these requisites will enable each uncrewed UAM flight operation under this ConOps to be capable of meeting legacy IFR connotations (i.e., definition of a pilot, pilot responsibilities, and pilot recommendations for ATC interactions), while being ultimately designed to support UAM scalability. Key enhancements to flight operations will be as follows:

> Takeoff and landing: UAM aircraft will use procedures that enable fully automated takeoffs and landings with vertically guided initial and final segments.

> Traffic spacing and sequencing: Using in-trail self-spacing and interval management practices based on standardized agreements with ATC and between operators for applicable in-trail procedural separation (taking foundation from legacy traffic management initiatives for IFR traffic).

> ATC communication: Two-way voice communication between ATC and Multi-Vehicle Supervisors will be provided by either a VHF ground relay or airborne vehicle C2 link or, as available, by low-latency, party-line Voice over Internet Protocol (VoIP) network communications.

> Energy reserve Recommendations: Robust contingency and emergency management capabilities, including high-fidelity monitoring of the energy state and consumption during flight, will enable an equivalent level of safety to the legacy IFR reserve concept."

The CONOPs for the dynamic design of corridors is presented in (MITRE 2019):

"The Dynamic Delegated Corridors (DDCs) concept is intended to enable UAM aircraft to operate in busy airspace by defining specific corridors that enable procedural separation from conventional aircraft operating under IFR flight rules. The concept also defines a set of rules and procedures to help coordinate traffic flows within that corridor. DDCs are volumes of airspace designated for flight using an established set of procedures and rules. DDCs are similar to the notion of VFR corridors and VFR flyways, except today's VFR corridors and flyways are rather static. The status of Dynamic Delegated Corridors will vary over time, enabling them to be opened and closed depending upon environmental conditions (e.g., wind, weather), UAM traffic density/demand, airport configurations, and legacy air traffic."

6.1 Mature Operations: Recommendations

All of the recommendations identified for Initial Operations Phase 2 (with remote pilots) and Midterm Operations need to be considered for Mature Operations. In addition, the following recommendations need to be considered:

Recommendation 6.1: Additional research is required to develop and demonstrate an ability to safely and effectively implement the multi-aircraft supervisor concept within the airspace structure assumed for Midterm Operations and continuing to be used in Mature Operations. (NASA m:N 2024). This will require significant automation support, including a communications infrastructure to support such operations.

Recommendation 6.2: The concept of dynamic design of new UAM corridors requires the definition of further detail regarding the concept and evaluation of proposed approaches to its implementation (MITRE 2019). This will also require significant automation support.

7.0 Prioritization of UAM Standards

This analysis of standards builds upon results reported in the Task 3 report for this project, which included a focus on UAM standards.

To provide further clarity regarding the standards needed to support the expected technology path, those existing standards that were identified and discussed in the Task 3 report for this project were evaluated. Along with those findings, additional standards that are needed for full implementation of UAM were identified and evaluated.

In Appendix B, results are provided prioritizing the need for such standards for the implementation of UAM based on a quantitative scoring methodology stated below. This prioritization provides a clear roadmap of standards development needs across key areas, offering actionable guidance for the FAA to focus future research and standards coordination efforts.

7.1 Prioritization of Standards

The quantitative scoring methodology uses a multi-criteria weighted evaluation procedure to categorize and prioritize technology standards gaps. This framework quantifies four primary evaluation criteria, each of which is assigned a different weight (w_1 through w_4) according to the operational reality and priorities of stakeholders. These criteria are: Safety Impact (w_1): where the potential severity of failure modes range from no impact to a catastrophic system failure; Operational Dependency (w_2): where the gap prevents core functionality versus simply failing to produce optimal performance; Time Criticality (w_3): which assesses the urgency of resolution relative to program milestones and the target for market entry; Implementation Complexity (w_4): where the technical, organizational, and regulatory complexity to resolving the gap is assessed, ranging from minor adaptation to a complex fundamental industry transformation.

All evaluative criteria follow a standard 0–10 scoring rubric with clear definitional criteria such that '10' denotes the most severe state (for example, catastrophic safety impact, prevents core operational capability, immediate action is required), compared to a minor adaptation would be scored a '0' would denote minimal impact. The overall prioritization score is calculated using the following formula:

where S_i represents the individual criterion score and w_i represents its corresponding weight, with the constraint that

$$\sum_{i=1}^{4} w_i = 1.$$

This adjustable weighting system provides a pathway to customize the framework based upon various technology areas such as communications, navigation systems, propulsion technologies, vertiport infrastructure, air traffic management systems, or autonomous flight controls. For example, safety-critical systems may have a higher weight (e,g., $w_1 = 0.40$) to give more emphasis to safety impact when compared to the operational dependency.

The framework takes the input from subject-matter experts, provides scores, and temporal stability checks to ensure prioritizations remain valid. This systematic approach shifts subjective gap assessments into a data-driven approach to support transparency in decision-making, resource allocations, and progress monitoring in the context across the full UAM technology development lifecycle.

7.2 Mathematical Formulation

Composite Score Calculation

$$\text{Total Score} = \sum_{i=1}^{n} S_i \times w_i \qquad (1)$$

where:

$$S_i = \text{Score for criterion } i \in [0,10] \qquad (2)$$

$$w_i = \text{Weight for criterion } i \qquad (3)$$

$$n = \text{Total number of criteria (4 in this case)} \qquad (4)$$

1

Weight Constraints

$$\sum_{i=1}^{n} w_i = 1 \quad \text{and} \quad 0 \leq w_i \leq 1 \quad \forall i$$

Criteria Definitions

Table 1. Criteria definitions.

Criterion	Weight	Description
Safety Impact	w_1	Severity of failure consequences
Operational Dependency	w_2	Degree of operational blocking
Time Criticality	w_3	Urgency for resolution
Implementation Complexity	w_4	Technical and organizational challenges

7.3 Scoring function

Based on its expertise, the team used a weighted scoring system to decide which gaps should have high priority and should be addressed first. The team scored each gap on four factors, using a 0–10 scale with clear rubrics for what each score means. This system would allow other subject matter experts to have a process to also categorize and prioritize the standards. Weights for each criterion could also be adapted to account for influencing factors outside of this research.

Safety Impact (35% weight) informs us of the severity of negative consequences should the gap not be fixed. A low score (around 2) means the impact is small. A high score (10) means the worst case — loss of control and multiple fatalities.

The following rubrics are used for detailed ranking in the Safety Impact Score.

Table 2. Rubric for evaluating safety impact.

Safety Impact		
Score	Risk Level	Remark
10	Catastrophic	Total loss of control, multiple fatalities likely
8	Hazardous	Significant reduction in safety margins, serious injuries
6	Major	Large reduction in safety margins, minor injuries
4	Minor	Slight reduction in safety margins, inconvenience
2	Negligible	No effect on safety

For Operational Dependency (25% weight), the scoring is calculated based on how much the gap affects UAM operations. A score near 2 means it will make the system efficient in a marginal way, while 10 means nothing can move forward until this is solved.

The following rubrics are used for detailed ranking in the Operational Dependency Score.

Table 3. Rubric for evaluating operational dependency.

Operational Dependency		
Score	Risk Level	Remark
10	Blocks all operations	Nothing can proceed without this
8	Blocks most operations	Only limited test flights possible
6	Limits scaling	Can operate but not at commercial scale
4	Reduces efficiency	Operations possible but suboptimal
2	Minor impact	Marginal impact

Time criticality (weight 20%) is the urgency of addressing the particular standards gap. For the commercial deployment of this identified must start now with an aim point of mid-2027. The scoring ranged from future capabilities ranging beyond 24 months to immediate action required (in the next 6 months).

The following rubrics are used for detailed ranking in Time Criticality Score.

Table 4. Rubric for evaluating time criticality.

Time criticality		
Score	Risk Level	Remark
10	Immediate (0-6 months)	Must start now for mid-2027 target
8	Near-term (6-12 months)	Critical path item
6	Medium-term (12-18 months)	Important but has buffer
4	Long-term (18-24 months)	Can wait for other developments
2	Future (24+ months)	Advanced capability

The implementation complexity (30%) addresses the estimate of the technical and organizational challenges involved in gap resolution. This can a score of 2 with straightforward implementation to a complex fundamental industry transformation score of 10.

The following rubrics are used for detailed ranking in Implementation Complexity Score.

Table 5. Rubric for evaluating implementation complexity.

Implementation Complexity		
Score	Risk Level	Remark
10	Extremely complex	Required fundamental industry changes -need attention
8	Very complex	Multiple stakeholder alignment needed
6	Complex	Significant technical challenges
4	Moderate	Known solutions need adaptation
2	Simple	Straightforward implementation

Each of these scores was combined using the weights above to get an overall priority for each gap. The categorization and prioritization of these standards are cataloged in Appendix B.

The findings of this report identified that current standards for UAM are largely fragmented and generally lacking when weighed against the potential for UAM to carry large volumes of passengers through dense urban landscapes. The classification system identified in Appendix B provides an additional layer to the research findings, laying the foundation for a detailed roadmap that distinguishes immediate priorities where gaps in standards must be addressed in the short term (high) from standardization efforts that may be delayed to address emergent trends in UAM.

This prioritization scheme emphasizes standards that have an immediate safety impact, set foundational dependencies, inform public trust and acceptance, and define critical operational norms. Lower priority standards may not represent a vital need or may be developed in time as technologies advance, and UAM concepts mature. While the findings of this research cannot directly steer policy or standardization efforts themselves, they provide a starting point for prioritizing standards so that more critical gaps are addressed more quickly. This is especially true when approaching airworthiness and certification aspects of UAM aircraft.

A critical component when prioritizing standardization efforts is how existing standards and known gaps may affect the ability of the UAM industry to comply with existing regulatory requirements. Standards may provide a flexible approach to defining a certification basis for novel aircraft using the 14 CFR §21.17(b) pathway. This pathway enables UAM aircraft manufacturers to establish a certification basis for their aircraft using applicable regulations (FAA, 2025). In some cases, this may include industry consensus standards, which may be used to define a means of

compliance. The incorporation of consensus standards into aircraft certification processes, which may be driven by risk-based metrics, may rely heavily on standards. This prioritization provides a starting point for addressing gaps.

In summary, prioritizing these standardization gaps provides a reasonable starting point for informing continued development of standards that influence a wide range of issues relating to UAM. These issues may be more critical, such as those surrounding cybersecurity, C2 links, and spectrum, or those that may not carry as much urgency, such as those surrounding protocols between certain aspects of automated systems. Overall, this prioritization provides a realistic starting point for continuing discussion regarding standard development.

8.0 RISK ASSESSMENT FOR UAM OPERATIONS

The Task 1 report for this project provides a review of several different approaches to risk assessment that have been identified. The Task 2 report then illustrates the application of three such approaches, two of them based on qualitative methods and one based on quantitative methods.

8.1 Qualitative Assessment of Risk for UAM Operations

In the Task 2 report for this project, six prominent qualitative risk assessment methodologies. These six methodologies were selected for inclusion based on three factors: *i)* their estimated scope of impact in the field of qualitative risk assessment; *ii)* their perceived relevance to UAM; and *iii)* their distinct and complementary natures.
Several of them were then applied to four UAM case studies. These six approaches were:
- Causal Analysis Using System Theory (CAST).
- Failure Mode and Effects Analysis (FMEA).
- Functional Resonance Analysis Method (FRAM)
- Influence Diagrams (ID).
- System-Theoretic Accident Model and Processes (STAMP).
- System-Theoretic Process Analysis (STPA).

8.1.1 Causal Analysis Using System Theory (CAST).

Causal Analysis Using System Theory, abbreviated as CAST, was developed by Professor Nancy Leveson (M.I.T.) as, quoting [Leveson CAST, 2019]:

> "a structured approach...to identify the questions that need to be asked during an accident investigation and determine why the accident occurred."

Importantly, CAST is intended as an analysis tool looking backward after an accident has occurred, while STPA, also developed by Professor Leveson, is intended as a proactive tool to identify and mitigate risks, *i.e.*, before accidents occur. Moreover, both CAST and STPA are safety analysis methods that integrate seamlessly with the STAMP framework.

A centerpiece of the philosophy of CAST is that investigators should seek to learn as much information about an accident as possible, rather than presume the existence of, and reductively search for, a singular "root cause." Professor Leveson terms this reductive approach "root cause seduction and oversimplification of causality."

The five (5) parts of a CAST analysis are shown in Figure 16. 16 (taken from [Leveson CAST, 2019]).
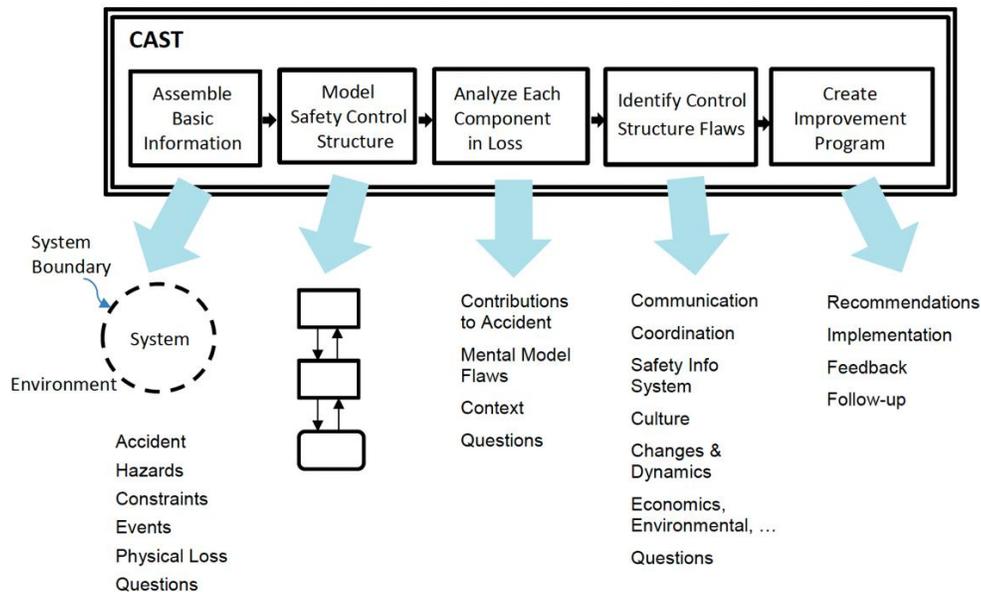
Figure 16. The five parts of a CAST analysis [Leveson CAST, 2019].

While CAST is included in the list of qualitative risk assessment methodologies reviewed in this report on account of its importance and applicability, it is not used in this report's applications of qualitative risk assessment to UAM because the authors do not have access to a specific UAM accident for analysis.

8.1.2 Failure Mode and Effects Analysis (FMEA).

Failure Mode and Effects Analysis (*e.g.*, [ASQ], [Stamatis, 2003], [Stamatis, 2015]), abbreviated as FMEA, is described by the American Society for Quality (ASQ) as follows:

> "Begun in the 1940s by the U.S. military, failure modes and effects analysis (FMEA) is a step-by-step approach for identifying all possible failures in a design, a manufacturing or assembly process, or a product or service. It is a common process analysis tool."

The general FMEA process involves many steps, which are not listed here, but which are described in detail in the above references. A critical part of the process involves completing an FMEA form (table), such as the one shown in Figure 17 (taken from [ASQ]). As shown in the figure, the FMEA process requires enumeration of functions, identification of each function's potential failure modes, the effects of those failures, the potential causes of those failures, the process controls, the recommended actions, the responsibility for those actions and the target completion date, and the achieved results of those actions.

Function	Potential Failure Mode	Potential Effects(s) of Failure	S	Potential Cause(s) of Failure	O	Current Process Controls	D	RPN	CRIT	Recommended Action(s)	Responsibility and Target Completion Date	Action Results					
												Action Taken	S	O	D	RPN	CRIT
Dispense amount of cash requested by customer	Does not dispense cash	Customer very dissatisfied Incorrect entry to demand deposit system Discrepancy in cash balancing	8	Out of cash	5	Internal low-cash alert	5	200	45								
				Machine jams	3	Internal jam alert	10	240	24								
				Power failure during transaction	2	None	10	160	16								
	Dispenses too much cash	Bank loses money Discrepancy in cash balancing	6	Bills stuck together	2	Loading procedure (riffle ends of stack)	7	84	12								
				Denominations in wrong trays	3	Two-person visual verification	4	72	18								
	Takes too long to dispense cash	Customer somewhat annoyed	3	Heavy computer network traffic	7	None	10	210	21								
				Power interruption during transaction	2	None	10	60	6								

Figure 17. An FMEA form example, from [ASQ].

The FMEA RA methodology is illustrated in an analysis below focused on flight planning and strategic deconfliction.

8.1.3 Functional Resonance Analysis Method (FRAM).

Functional Resonance Analysis Method (*e.g.*, [Hollnagel, 2016], [Patriarca, 2020]), abbreviated as FRAM, was developed by Professor Erik Hollnagel. The following quote from [Hollnagel, 2016] helps position FRAM relative to other RA methodologies:

> "...FRAM is a method to analyse how work activities take place either retrospectively or prospectively. This is done by analysing work activities in order to produce a model or representation of how work is done. This model can then be used for specific types of analysis, whether to determine how something went wrong, to look for possible bottlenecks or hazards, to check the feasibility of proposed solutions or interventions, or simply to understand how an activity (or a service) takes place. The FRAM is a method for modelling non-trivial socio-technical systems. It is NOT a risk assessment method and it is not an accident analysis method. Neither is a FRAM model a flow model, a network model, or a graph. But the model produced by a FRAM analysis can serve as the basis for a risk analysis, an event investigation, or for something entirely different."

A FRAM analysis consists of the following steps, taken from [Hollnagel, 2016]:

1. "Identify and describe essential system functions, and characterise each function using the six basic characteristics (aspects). In the first version, only use describe the aspects that are necessary or relevant. The description can always be modified later.
2. Check the completeness / consistency of the model.
3. Characterise the potential variability of the functions in the FRAM model, as well as the possible actual variability of the functions in one or more instances of the model.

4. Define the functional resonance based on dependencies / couplings among functions and the potential for functional variability.
5. Identify ways to monitor the development of resonance either to dampen variability that may lead to unwanted outcomes or to amplify variability that may lead to wanted outcomes."

A critical part of FRAM is the specification of the six FRAM aspects (Step 1, above) to trigger a system function, as illustrated in Figure 18 taken from [Hollnagel, 2010].
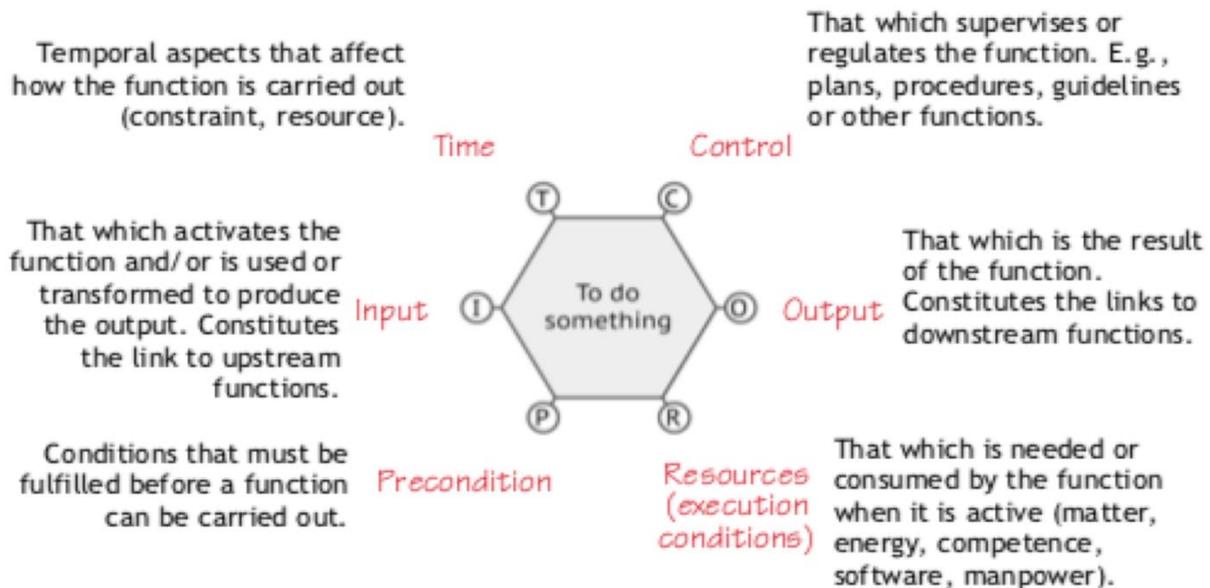
Figure 18. The six FRAM aspects of a function, from [Hollnagel, 2010].

FRAM is not explicitly used in any of the four applications illustrated below.

8.1.4 Influence Diagrams (ID).

Influence Diagrams (*e.g.*, [Shachter, 1986], [Howard, 2005], [Pearl, 2005]), abbreviated as ID, were developed in the 1970s out of the (quantitative) decision analysis research community. Quoting from [Howard, 2005], an influence diagram:

"...is at once both a formal description of the problem that can be treated by computers and a representation easily understood by people in all walks of life and degrees of technical proficiency. It thus forms a bridge between qualitative description and quantitative specification."

As the quote makes clear, influence diagrams are at the intersection between qualitative and quantitative RA methodologies. In this paper, they are classified as qualitative methodologies, but are employed in close alignment with the quantitative methodology of decision analysis.

The ID risk assessment methodology is employed in the analysis below on flight planning and strategic deconfliction, along with FMEA.

8.1.5 System-Theoretic Accident Model and Processes (STAMP).

System-Theoretic Accident Model and Processes (*e.g.*, [Leveson STAMP, 2002], [Leveson STAMP, 2020], [Zhang, 2022]), abbreviated as STAMP, was developed by Professor Nancy Leveson (M.I.T.) as an accident model and process framework. Notably, it is *not* by itself intended for accident *analysis*, but is, instead, intended to serve as a "base layer," which may be profitably integrated with an accident analysis methodology, such as CAST (see above) or STPA (see below).

The following quote (from [Leveson STAMP, 2002]) highlights the philosophy of STAMP:

> "Accidents (loss events) occur when external disturbances, component failures, and/or dysfunctional interactions among system components are not adequately controlled, i.e., accidents result from inadequate control or enforcement of safety-related constraints on the development, design, and operation of the system.
> ...Safety is managed by a control structure embedded in an adaptive socio-technical system. The goal of the safety control structure is to enforce safety-related constraints (1) on system development, including both the development process itself and the resulting system design, and (2) on system operation.
>
> In this framework, understanding why an accident occurred requires determining why the control structure was ineffective. Preventing future accidents requires designing a control structure that will enforce the necessary constraints."

Figure 19, from [Leveson STAMP, 2020], illustrates the role of STAMP within the broader context of accident and hazard analysis.
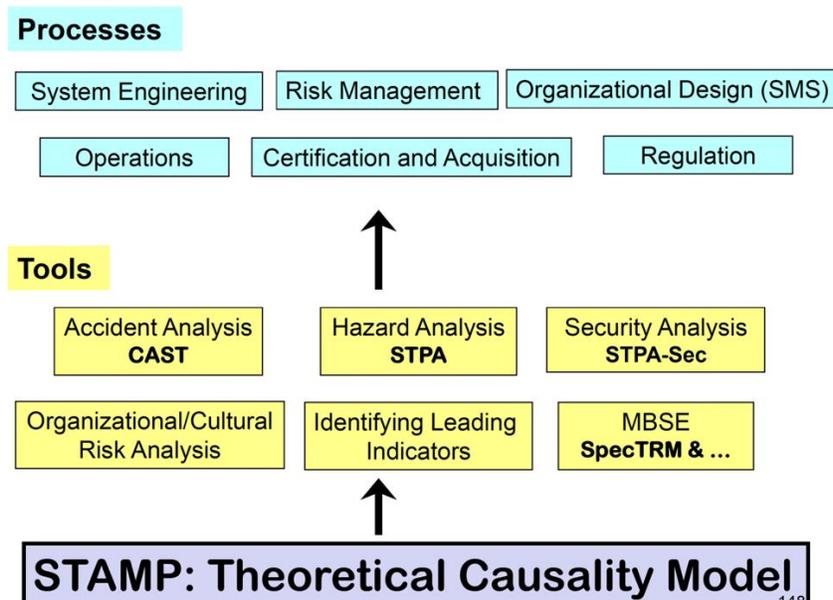
Figure 19. STAMP forms the basis for accident and hazard analysis [Leveson STAMP, 2020].

The three components of STAMP are: *i)* safety constraints, *ii)* hierarchical safety control levels, and *iii)* process control loops. In particular,

1. Safety constraints "specify those relationships between system variables that constitute the nonhazardous system states" [Leveson STAMP, 2002].
2. Hierarchical safety control levels capture the fact that "socio-technical systems can be modeled as a hierarchy of levels of organization with control processes operating at the interfaces between levels to control processes at the lower levels" [Leveson STAMP, 2002].
3. Process control loops "between the various levels of the hierarchical control structure create or do not handle dysfunctional interactions leading to violations of the safety constraints" [Leveson STAMP, 2002].

STAMP, as a basis underlying STPA, is employed in the analysis in Section 2.2.3 (Autonomous C2) and Section 2.2.4 (Human-Automation Interaction and Human-Human Interaction).

8.1.6 System-Theoretic Process Analysis (STPA).

System-Theoretic Process Analysis (*e.g.*, [Leveson STPA, 2018]), abbreviated as STPA, is a hazard analysis technique created by Professor Nancy Leveson (M.I.T.). The novelty of STPA, relative to other hazard analysis techniques, is that it is (quoting from [Leveson STPA, 2018]):

"...based on an extended model of accident causation. In addition to component failures, STPA assumes that accidents can also be caused by unsafe interactions of system components, none of which may have failed."

As mentioned above, *i)* STPA builds upon and integrates with the accident modeling methodology of STAMP, and *ii)* STPA is a (forward-looking, anticipatory) hazard analysis technique, while CAST, which also builds upon STAMP, is a (backward-looking, post-mortem) accident analysis technique.

Figure 20 shows the four steps of the STPA method (from [Leveson STPA, 2018]).
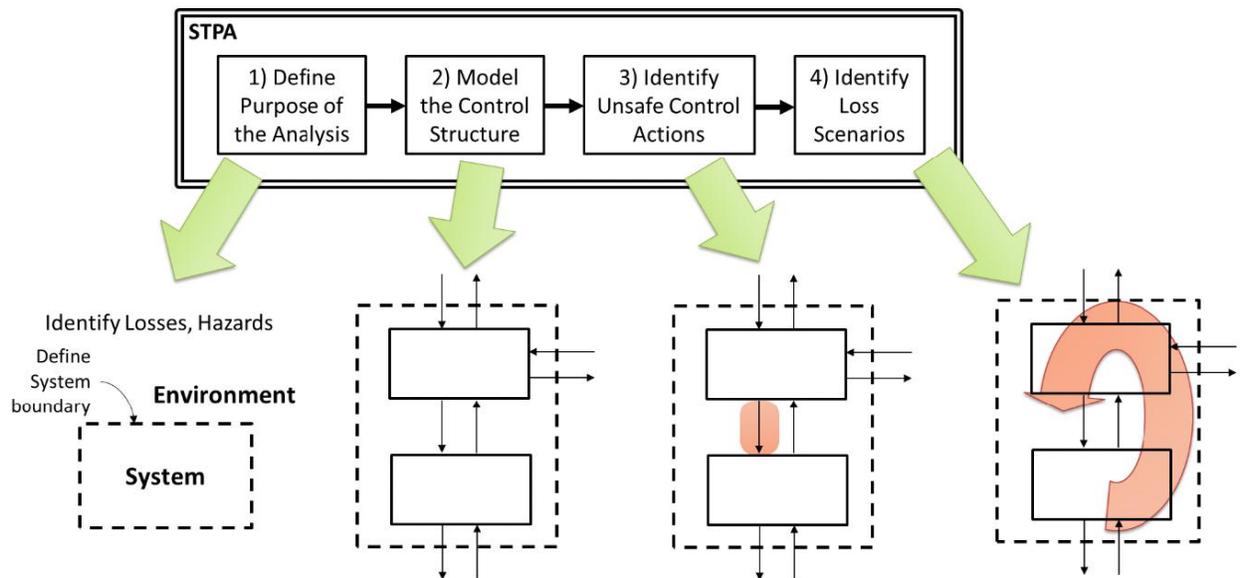
Figure 20. STPA method overview, from [Leveson STPA, 2018].

The asserted advantages of STPA, relative to other hazard analysis techniques, are its capabilities (summarizing Leveson STPA, 2018) to:
1. Analyze very complex systems.
2. Integrate in early concept analysis.
3. Include software and human operators in the analysis.
4. Provide documentation of system functionality.
5. Integrate into system engineering processes.

STPA, building upon STAMP, is employed in an analysis of an autonomous C2 system along with a discussion of human-automation interaction and human-human interaction.

8.1.7 Application of Specific Qualitative RA Methodologies to UAM Systems. XXX

While Section 8.1 briefly summarizes the selected qualitative risk assessment methodologies, this section applies them to different aspects of UAM hazard analysis. These applications demonstrate the diverse ways qualitative risk assessment methodologies may be applied to different aspects of UAM systems. In particular, Section 8.1.7.1 uses both FMEA and ID in an integrated manner, while Sections 8.1.7.2 and 8.1.7.3 use STAMP and STPA, again, in an integrated manner.

8.1.7.1 Detect and Avoid (DAA) Systems, Propulsion Systems, and Vertiport Operations.

This first example of qualitative risk assessment in the context of UAM focuses on three key areas of UAM design and operations, namely: *i)* detect and avoid systems, *ii)* propulsion systems, and *iii)* vertiport operations.

To ensure a holistic approach to hazard identification, the researchers identified hazards and outcomes/harms associated with various failure scenarios and provided an analysis of the initial risk associated with each failure based on SMEs. Furthermore, researchers evaluated existing standards and used them to determine the risks associated with each failure more accurately. Lastly, the team identified current and future datasets that may further assist in providing more quantitative risk assessments. These datasets may assist researchers in further identifying gaps in standards/regulations/procedures and developing new datasets in future research.

Scenario: Highlighting Systems Integration. The scenario is built to identify the primary and subsequent failures of the related subsystems. The scenario assumed flights took place under an established CONOPS, starting from a small rural town near an interstate system and connecting to a larger metropolitan hub where air service could continue through traditional airlines such as Delta or American Airlines.

This service entertained the model of legacy airlines supporting UAM operations by allowing customers to purchase tickets that would fly them from a small rural community to a metropolitan airport to transfer to existing airlines in a traditional airport environment. The CONOPs assumed flights originated in Class G (uncontrolled) airspace and arrived at an airport with a control tower within a STPA. Furthermore, the scenario considered air traffic management, communication in a complex environment, and operation within existing aviation infrastructure.

The CONOPs assumed that all aircraft have some equivalent of *i)* ADS-B in and out; *ii)* Detect and Avoid (DAA) systems that function per established consensus standards; and *iii)* automation to fly specified routes, departures, arrivals, taxiing on existing taxiways, and to fly contingency

routes in case of an emergency. Predefined corridors restricted the airspace environment, and circular holding patterns around vertiports were predefined. Lastly, the flight planning required a flight operator to submit the proposed flight plan, indicating acceptable ranges for parameters, and submit proposed contingency flight plans. The software was available to evaluate the proposed flight plans. The scenario assumed Air Traffic Management (ATM) involvement and requisite training to expect the same standards for UAM vehicles as those of existing commercial aircraft. In this scenario, UAM vehicle propulsion systems met or exceeded current airworthiness standards for aircraft carrying passengers for hire.

Scenario Specification. The details and specifications of the scenario described in the previous section are as follows.

Thompson Vertiport: Located in Grand Forks County, the Thompson Vertiport is located approximately 5 miles south of Grand Forks, ND, and 2 miles east of Thompson, ND. It is 2,000 feet east of Interstate 29 at Exit 130.

Fargo Vertiport: The Fargo Vertiport is in Cass County at the North General Aviation Ramp west of the Fargo Jet Center and east of the Arm/Disarm Pad at Hector International Airport. It is directly north of taxiway C3.

Flight Profile Departure Procedures:
Take off from Thompson Vertiport.
Heading 145 degrees for 3 nm to waypoint 1 (latitude 48.73184, longitude -98.02162).
Heading 167 degrees for 49 nm to Hector International Airport.

Flight Profile Arrival Procedures:
Contact Fargo Approach 10nm north of the field.
Contact the tower before entering Class D airspace.
Use existing runways as vectors for low-level flight to taxiways.
Taxi (low-level flight) to vertiport using existing taxiways and General Aviation ramp.
Land at Fargo Vertiport.

The aircraft can fly the Thompson to Fargo route in 25 minutes.

Altitude and Airspeed:
Vertiport Operations - below 400 feet AGL.
Enroute operations - approximately 1500 – 4000 feet.
Lilliam eVTOL - max airspeed 155 mph - Thompson to Fargo route flown in 23 minutes.
Joby eVTOL - max airspeed 200 mph - Thompson to Fargo route flown in 18 minutes.
Archer Midnight eVTOL – cruise speed 150 mph, cruise altitude 2,000 feet.

Risk Assessment Method Used. In the ASSURE research project A25: Develop Risk-Based Training and Standards for Waiver Review and Issuance [Snyder, 2021], the team developed a prototype framework to address the consistency problem with Beyond Visual Line of Sight (BVLOS) waiver submission and review guidelines. The research team tested the results of this

framework against an approved BVLOS waiver for validation purposes and conducted a tabletop exercise with key FAA stakeholders and multiple universities.

This framework created a list of key hazards associated with BVLOS waiver applications, laying a solid foundation for identifying potential failures for UAM operations. The team modified the framework from the traditional safety risk assessment requirements outlined in FAA's Order 8040.4C Safety Risk Management Policy (SRMP) [FAA 8040.4C] to meet the specific objectives of the current research project. As part of this modification, the initial risk associated with the outcome-harm noted in each column was evaluated based on the risk matrix charts for the FAA's Order 8040.6A and SMS Manual December 2022 for Air Traffic Organization (2022). While known gaps in standards exist because UAM is not yet a reality within the National Airspace System (NAS), the researchers evaluated existing standards cataloged as part of the ASSURE research project *A37: UAS Standards Tracking, Mapping, and Analysis* [Snyder, 2022] to identify existing mitigations related to each hazard and outcome/harm. This informed the SMEs on the failed system or subsystem's maturity and assisted the SME-based qualitative assessment of the risk associated with each hazard. This also provided a baseline for existing consensus standards to inform future research tasks requiring the identification of gaps in consensus standards. After identifying the initial risk associated with each identified outcome or harm, the researchers began to identify existing datasets and those needed to provide a more quantitative assessment instead of a qualitative one.

After addressing the hazards that were identified through previous research under A25 [Snyder, 2021], the researchers continued to evaluate additional hazards associated with the scenario using other resources, such as:
1. FAA Order 8040.6A "Unmanned Aircraft Systems (UAS) Safety Risk Management (SRM) Policy" [FAA 8040.6A], in particular, Appendix B of that report on "UAS Hazards, Mitigations, and Outcomes".
2. Lange, "Modeling a System of Systems for Advanced Air Mobility" in the *Journal of Air Transport Management* [Lange, 2024];.
3. Arel, "Safety Management System Manual," by *Air Traffic Organization* [Arel, 2022].

These resources further refined possible fundamental failure modes within the scenario(s). Lastly, researchers assigned each hazard a category. This enabled additional sorting and analysis of the data. The team organized hazards into five categories for evaluation:
1. Technical Issue UAS
2. Human Error
3. Adverse Operating Conditions
4. Unable to See and Avoid
5. UAS Operations

Critical systems evaluated by the team were DAA, propulsion, and vertiport-related.

Results of Safety Risk Analysis (SRA). Based on the five key categories listed in the previous section, the research team identified 76 hazard conditions. For each hazard condition, SMEs identified the most credible outcome or harm. While conducting the risk assessment based on the risk matrix charts for the FAA's Order 8040.6A and SMS Manual December 2022 for Air Traffic Organization (2022), the risk value varied based on what risk matrix chart used. This variance

further validated the need for a more objective, quantitative risk assessment method. Of the 76 hazard conditions, researchers linked 156 existing standards and procedures to the various hazard conditions and listed them as mitigations to reduce the risk associated with the outcome or harm. Many existing standards or procedures appeared for multiple entries, reflecting the importance of that standard or procedure to maintain safety and mitigate risk. It also identified the lack of existing standards or procedures related to many credible outcomes that could result from the hazards identified.

This risk assessment, in the form of a Microsoft Excel spreadsheet, is available as an attachment to Report 3 for this project.

It was further determined that few quantitative datasets are available to identify the likelihood or probability of failures to validate subject matter experts' determinations.

Benefits and Shortcomings of Risk Assessment Methodology. The standardization roadmap created in A25 [Snyder, 2021] captures the benefits of this SRA process. This roadmap aided in identifying potential hazards requiring mitigation before any FAA approval. It also created a standardized process, allowing the FAA to add and track hazards and outcomes over time to provide the greatest availability of data to determine the probability of various types of failure. In addition to this, as the use of the UAS Aviation Safety Reporting System reports increases and the FAA continues to mine the data to track common failures related to UAS accidents, the hazard list can become more accurate and refined. The FAA may also require applicants to address additional hazards for future approvals. This could improve the SRA process and impact aircraft certification and approval for various UAM operations.

The shortcoming of this method is standardizing the safety assurance process. To date, the FAA still needs to provide a clear path for safety assurance for operators. Approvals gained by traditional risk assessments often get approval to fly, but they do not identify the safest way to fly or ensure continuous improvement. For example, FAA waiver approvals for BVLOS operations do not require reporting after the flight activity to verify what risk mitigation strategies worked and which did not, nor are operators required to identify what mitigation strategies had unintended consequences. This creates potential scenarios where mitigations may increase the overall risk instead of reducing the risk in the approved UAS operation, and these conditions may go unreported. Currently, the SRA system relies heavily on subject matter experts to determine the initial risk with existing mitigations and identify the residual risk after implementing mitigations before a given operation. The fact that the same individuals flying the UAS often conduct safety risk assessments, individuals who often do not have the proper training and may be more concerned with production than protection, may also impact results.

8.1.7.2 Flight Planning and Strategic Deconfliction.

The second application of qualitative risk assessment methodologies to UAM is focused on planning and strategic deconfliction.

Description and Overview. The goal of the analyses presented below is to illustrate the use of two of the qualitative risk assessment methodologies reviewed earlier, namely, Influence Diagrams (IDs) and FMEA, in order to explore the use of these qualitative safety risk assessments in an

evaluation of UAM operations. The focus of this sample analysis will be flight planning and strategic deconfliction, with attention to the impact of communications.

To perform the analyses described below, it is necessary to specify the relevant CONOPS.

Actors

The CONOPS includes the following five (5) types of actors:
1. PSU: There is one (1) PSU for the urban area. The PSU includes a PSU manager and support staff, including a local meteorologist or an individual with the necessary meteorology expertise.
2. A traffic manager responsible for Traffic Management Functions (TMFs) for strategic deconfliction.
3. Vertiports: there are multiple (say, *M*) vertiports located in and around the metropolitan area. Each vertiport can accommodate multiple (say, *X*) aircraft and is staffed with: *i)* multiple (say, *N*) landing/departure managers, *ii)* one (1) vertiport manager, *iii)* one (1) maintenance specialist, and *iv)* one (1) communications specialist. Vertiport staff will have access to meteorology expertise as well.
4. Additional landing pads: There are multiple additional landing pads for single aircraft located in and around the metropolitan area. Each will be staffed with someone responsible for managing the operations of that specific landing pad.
5. Flight operators: there are multiple flight operators, including *i)* one (1) dispatcher/flight planner for each larger operation and *ii)* multiple RPICs per vertiport.

Missions

The CONOPS missions consist of passengers and cargo delivered to and from the *M* vertiports.

Aircraft

The CONOPS aircraft are assumed to have the following six (6) properties and capabilities:
1. All aircraft are rotorcraft.
2. All aircraft are remotely piloted.
3. There is a single remote pilot per UAS.
4. All aircraft have some equivalent of ADS-B Out and ADS-B In.
5. All aircraft have radar and vision systems to support DAA and provide RPIC situation awareness.
6. All aircraft are equipped to fly autonomously, including the capabilities to: *i)* fly planned routes (including route changes issued from the ground or autonomous changes if communications are lost while enroute); *ii)* depart and land; *iii)* support DAA; and *iv)* fly contingency routes.

Airspace

The CONOPS airspace has the following two (2) properties: *i)* flights are restricted to predefined corridors unless given an explicit exception; and *ii)* circular holding patterns around vertiports are predefined.

Airspace and Vertiport Demand

It is assumed that the CONOPS has to function in an environment where airspace and vertiport demand is high relative to capacity.

Flight Planning

The CONOPS flight planning sequence consists of the following five (5) steps:
1. The traffic manager responsible for TMF initiates temporary TFRs.
2. The flight operator (dispatcher) submits the proposed 4D flight plan, including an indication of acceptable ranges for parameters.
3. The flight operator (dispatcher) submits the proposed contingency flight plans, including an indication of acceptable ranges for parameters and planned alternate sites for landing.
4. Pre-flight, the software evaluates the proposed flight plan, including contingency plans, for the traffic manager responsible for TMF, i.e., the software performs strategic deconfliction of the 4D trajectory, based on four factors: *i)* TFRs (airspace and vertiport constraints); *ii)* aircraft DAA capabilities; *iii)* the already approved flight plans; and *iv)* rules of the road.
5. Enroute, the software continuously reevaluates the 4D trajectories, vertiport availability, and the status of all enroute aircraft.

Air Traffic Control (ATC)

The CONOPS includes ATC with FAA controller involvement under the following two (2) exceptions: *i)* the UAS enters controlled airspace as part of a planned mission; or *ii)* the UAS enters controlled airspace as a result of an off-nominal unplanned operation.

Communication Enablers

The CONOPS assumes primary and backup communication systems are supported and seamlessly accessed in all UAM aircraft. Voice vs. digital communication will have to be considered. These communication networks might take advantage of the following three (3) technologies and protocols:
- Internet Protocol (IP). The principal protocol for online communications is Internet Protocol. This set of rules is foundational in how the Internet works. But, despite its widespread use throughout the world, until recently, IP has played little part in communications within the aviation sector. Recently, there has been a push at the international level to migrate air traffic communications to an IP-based system, referred to generally as the Internet Protocol Suite. The drive for change came initially from ICAO but more recently has been spearheaded by the standards agencies for aviation technology, most notably the European Organization for Civil Aviation Equipment.
- Aviation Equipment (EUROCAE) and the Airlines Electronic Engineering Committee. Migrating to Internet Protocol Suite is a central component of the larger-scale project of modernizing ATM, which is being undertaken in Europe as the EU's Single European Sky ATM Research joint project and in the USA as the FAA's NextGen program.
- Supporting IP communications, VHF Data Link mode 2 (VDL2) is a new wireless transmission mode used on aircraft for sending short messages and position data. VDL transmission operates as a single carrier half-duplex and employs time-division duplexing, where uplink and downlink typically use the same frequency, similar to modern Wi-Fi systems [Jamal, 2020]. The frequency band (25 kHz) and time-division duplexing enable

robust operations in a dense urban environment. However, VDL2 has known gaps for lower altitude flight, which is where UAM operations would happen.

As a backup communication system, satellite communication for UAM will be useful for offshore or remote locations, away from typical ground stations, and as a backup if there is a failure of thenetwork. Some proponents suggest that satellite communication should actually be a primary means of communication. Additionally, satellites will provide a tracking mechanism for situational awareness for airspace owners for BLOS operations in dense urban environments [Duquerroy, 2021]. For this analysis, what is important is that two complementary high-reliability communications networks are integrated to serve as primary and backup systems for air-to-ground and air-to-air communications [Erturk, 2020]. For this analysis, what is important is that two complementary high-reliability communications networks are integrated to serve as primary and backup systems for air-to-ground and air-to-air communications [Erturk, 2020].

Potential Root Causes of Failures and of Potential Contributing Factors. To identify potential root causes, FMEA [ASQ] was applied. Figure 21 shows the results for strategic deconfliction. Note that potential failure modes (Column B) are specified at the level of outcomes that could, in turn, combine with other factors to result in an undesirable outcome.

Organization Ohio State University					Failure Mode and Effects Analysis							FMEA ID #
System Component Strategic Deconfliction					Design or Process Responsibility				Prepared by and their Title			
Process/Design					Team Members				FMEA Creation Date			
Process Step/Input or Design Item	Potential Failure Mode	Potential Enablers/Contributors	Potential Effect(s) of Failure	S E V	Potential Cause(s) / Mechanism(s) of Failure	O C C	Current Process Controls to Prevent Failure Mode	Current Process Controls to Detect Failure Mode	D E T	R P N	Recommended Actions	Person/Org Responsible for Actions
1. Strategic deconfliction	TFR: Overestimation of vertiport capacity	Lack of suitable alternative landing site	Inadequate estimation of vertiport capacity resulting in the need for diversion of an aircraft. If the contingency plan to handle such a diversion is inadequate, then an emergency landing may be required	9	Inaccurate weather forecast; inadequately trained and experienced PSU traffic manager and vertiport operator; lack of access to trained meteorologist	2	See Attachment X	See Attachment X	1	1 8	See Attachment X	PSIU, Dispatch; RPIC; Vertiport
1. Strategic deconfliction	TFR: Underestimation of vertiport capacity		Unnecessary delays; reduced throughput		Inaccurate weather forecast; inadequately trained and experienced PSU traffic manager and vertiport operator; lack of access to trained meteorologist					0		
1. Strategic deconfliction	TFR: Overestimation of airapce (corridor) capacity	Lack of suitable alternative trajectory; high demand for airspace	Inadequate safety eval. of proposed 4D trajectory for a flight		Inaccurate weather forecast; inadequately trained and experienced PSU traffic manager; lack of access to trained meteorologist; brittleness of strategic deconfliction software							
1. Strategic deconfliction	TFR: Underestimation of airspace (corridor) capacity		Unnecessary delays; reduced throughput;		Inaccurate weather forecast; inadequately trained and experienced PSU traffic manager; lack of access to trained meteorologist; brittleness of strategic deconfliction software							
1. Strategic deconfliction	Inadequate evaluation of airspace restrictions	Inadequate tactical replanning	Inadequate safety eval. of proposed 4D trajectory for a flight		Inaccurate weather forecast; inadequately trained and experienced PSU traffic manager; brittleness of strategic deconfliction software							
1. Strategic deconfliction	Incorrect assumptions about obstructions		Inadequate safety eval. of proposed 4D trajectory for a flight		Iinadequately trained and experienced PSU traffic manager; brittleness of strategic deconfliction software; out of date data on obstructions							
1. Strategic deconfliction	Incorrect assumptions regarding trajectories and contingency plans for other previously approved and upcoming flights	High demand for airspace and/or vertiports	Inadequate safety eval. of proposed 4D trajectory for a flight		Inadequately trained and experienced PSU traffic manager; brittleness of strategic deconfliction software							
1. Strategic deconfliction	Inadequate assumptions about performance capabilities of new flight and all other potentially interacting flights (including DAA capabilities)		Inadequate safety eval. of proposed 4D trajectory for a flight		Inadequately trained and experienced PSU traffic manager; brittleness of strategic deconfliction software; inadequate data input from flight operator regarding aircraft and automation capabilities							
1. Strategic deconfliction	Inadequate potential trajectory conflict evaluation (DAA) algorithm	High volume and complexity in airspace usage	Inadequate safety eval. of proposed 4D trajectory for a flight		Brittleness of DAA algorithm(s); inadequate data input from flight operator regarding aircraft and automation capabilities							
1. Strategic deconfliction	Inadequate safety evaluation of proposed 4D trajectory for a flight	High volume and complexity in airspace and vertiport usage	Inadequate safety eval. of proposed 4D trajectory for a flight		Inadequately trained and experienced PSU traffic manager; brittleness of strategic deconfliction software; brittleness in DAA algorithm(s) inadequate data input from flight operator regarding aircraft and automation capabilities							

Figure 21. FMEA analysis for strategic deconfliction supporting UAM.

Figure 22 provides an ID ([Howard, 2005], [Shachter, 1986]) indicating factors that could interact to affect the safety of a flight. It indicates that there are several contributing factors that could interact with the approval of a 4D trajectory and associated contingency plan for a new flight, and consequently influence the level of risk.

It further indicates that there are a number of factors that could interact to affect safety, such as the actual weather encountered by this new flight while enroute, the results of the preflight inspection, the performances of the aircraft used for this flight and of other aircraft, the dissemination of TFRs by a traffic manager responsible for TMFs, and the performances of the RPIC, Dispatcher/flight planner (if any), PSU, vertiport, and ATC (if the flight enters ATC controlled airspace). It also indicates that FAA regulations and/or Community-Based Rules represent a second-order factor that has an influence on things such as aircraft performance.

Figure 23 illustrates how additional detail can be added as input to the primary nodes shown in the influence diagram.
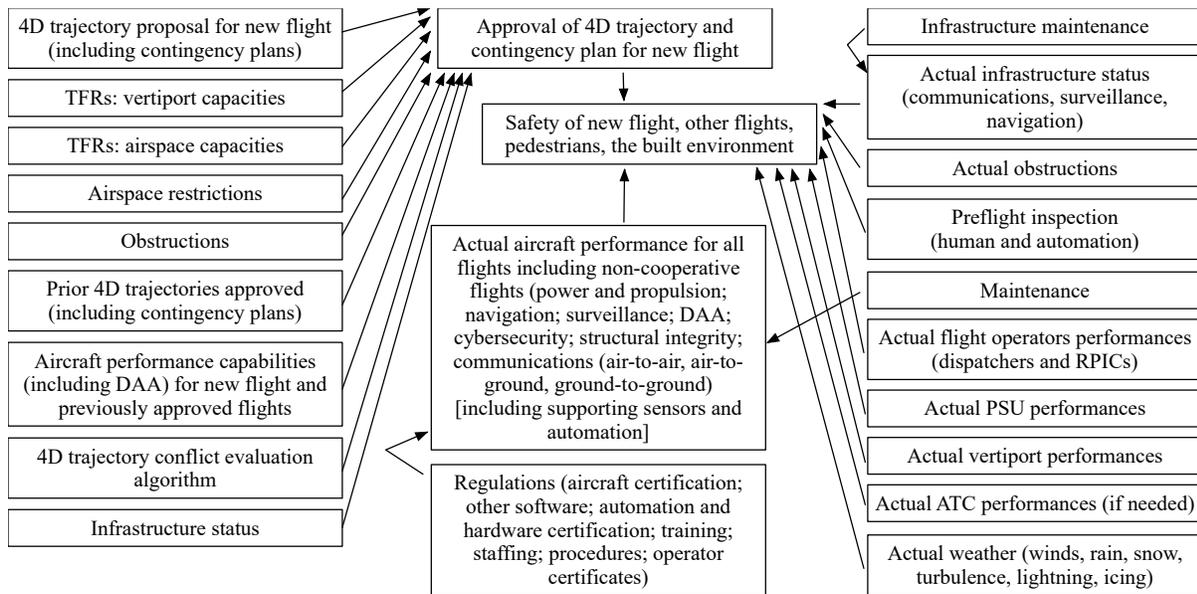
Figure 22. ID indicating factors that could interact to affect the safety of an UAM flight.
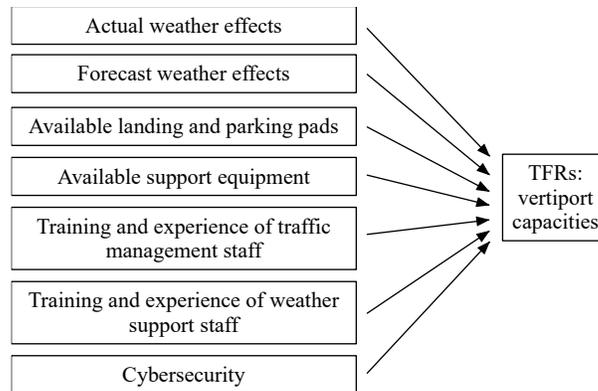
Figure 23. Factors influencing the capacity of a vertiport.

Interactions of the System with other Systems within Background Report Areas. Subsystems or products included in the A64 Task 1 background report [Rice, 2023] relevant to UAM were identified. These were used as probes for knowledge elicitation, asking: "How should the potential performance of some other subsystem or product be considered during the evaluation regarding strategic deconfliction for a proposed flight?" The process for strategic deconfliction should consider potential concerns associated with these other subsystems to evaluate the potential for an adverse outcome. These factors were included in the ID in Figure 22. Such concerns are listed below:

1. Detect and avoid. This is critical to strategic deconfliction. Judgments regarding the acceptability of a given proposed 4D trajectory and its associated contingency plan have to take into consideration:
   a. The ability of the involved aircraft to detect and avoid other aircraft and flying objects (including birds) and to detect and avoid built objects and terrain.
   b. The degree of uncertainty that needs to be assumed regarding the 4D trajectories for other aircraft (due to factors such as winds or the performance capabilities of those aircraft).
2. Power and propulsion. The potential for the aircraft to have a partial or full loss of power and/or propulsion needs to be considered as part of the assessment of the contingency plans associated with this new proposed flight. This could include situations where the aircraft can no longer maintain its planned 4D trajectory, as well as scenarios involving emergency landings. This possibility needs to be considered in developing and evaluating contingency plans.
3. Airspace and vertiport design. Airspace design will determine crossing points within the corridor network. Airspace design will also segregate flights based on their direction through a corridor (via altitude or lateral separation). Passing lanes will be incorporated to deal with flights flying at different speeds. Holding patterns around vertiports will provide a structured method to delay landing when necessary. Vertiports may have multiple landing pads. These structural specifications will place constraints on flight plans and DAA and will determine the buffers available to deal with off-nominal events and deviations from flight plans. These constraints need to be considered in strategic deconfliction.

4. Communications. Potential loss of communication by an individual aircraft, by a specific vertiport or PSU, by the traffic manager responsible for TMFs, by ATC, or by the UAM communications network as a whole need to be considered. This applies to communications with the RPIC and supporting operations center, as well as communications among these other entities. Contingencies to deal with this need to be considered in strategic deconfliction.

5. Navigation and surveillance. Regarding navigation, RNP capability associated with each flight is an important consideration for strategic deconfliction and interacts with the aircraft's DAA capabilities. If that aircraft capability should degrade without the knowledge of the software and the traffic manager responsible for strategic deconfliction, the potential for a loss of separation could increase. Surveillance is critical. If surveillance capabilities are degraded or lost for an individual aircraft or for a ground operator, such as at a PSU or vertiport, this has major safety implications. If a more widespread loss of surveillance occurs, this is even more significant in terms of safety. Strategic deconfliction needs to consider such possibilities in evaluating a contingency plan.

6. Standards, regulations, certification, and policy. Strategic deconfliction needs to evaluate a given flight plan and associated contingency plans relative to the requirements. They must be adequately specified to ensure that compliant strategic deconfliction is safe.

7. CONOPs and system architecture. The assumptions regarding the CONOPS have been specified above. If this CONOPS and the supporting system architecture specified change some of the specified assumptions (such as whether or not the aircraft is controlled remotely), then assumptions about how various factors influence safety will change.

8. Autonomous command and control. If the aircraft is fully autonomous or enters an autonomous mode due to loss of communications, appropriate contingency plans are necessary to ensure safety and need to be evaluated as part of strategic deconfliction.

9. Human-automation interaction and human-human interactions. Strategic deconfliction needs to consider the potential of inappropriate human-automation or human-human interactions. This includes all of the people potentially involved, as well as the specific systems in use by each person.

Description of the Relevant Environmental Factors for this System. Contingency plans need to consider the potential impact of all possible "environmental" factors. This includes factors that could affect an aircraft along its flight path or that require vectoring off the planned flight path, such as convective weather and winds, icing, birds, and obstacles introduced by the built environment. It could also include factors that impact the performance of ground personnel, such as lightning restricting activities of personnel at a vertiport or a fire, tornado, or some other emergency affecting personnel at a flight operations center, a PSU, or a vertiport.

Decomposition of the System into Sub-Systems. Strategic deconfliction is a function of a TMF with global responsibilities for UAM operations within an urban area. Given the complexities of such a planning function, software support is necessary. However, given the nature of some of the contributing factors that need to be considered in such planning (such as convective weather), this software needs to provide decision support for responsible humans.

There are several components of the decision-making process for strategic deconfliction that need to be integrated, including:
1. Data regarding aircraft capabilities for a proposed flight, including its RNP and DAA capabilities (or compliance with some minimum requirements for all flights).
2. Software that can evaluate a proposed 4D trajectory and its associated contingency plans within the corridor network for a flight based on consideration of other already approved 4D trajectories for other flights, including manned aircraft, as well as a topographical map indicating built structures. TFRs must also be considered by this software.
3. Human input (by the traffic manager responsible for TMFs) to generate TFRs; dispatcher(s)/flight planner(s) for large flight operations; RPICs for individual flights), to develop and submit proposed 4D trajectories and contingency plans and to provide the input necessary for the software to evaluate a proposed 4D trajectory and set of contingency plans for a flight. If the number of flights and complexity of the routes within the corridor network is sufficiently complex, then the assumption is that human input is provided to the software, which then makes the assessment (but with the ability of the human to override the software by exception).

Description of Potential Failure Stories for the System: Scenario 1. Two scenarios are presented that are informed by considering the implications of the influence diagram on failure modes identified as part of the FMEA analysis for strategic deconfliction. This highlights the potential value of using the influence diagram to provide a structured method to explicitly identify factors that could interact with the failure modes identified for strategic deconfliction.

The first scenario illustrates the use of the FMEA analysis focused on the reliance of strategic deconfliction on the specification of TFRs. It highlights the interactions of several factors identified in the ID in **Error! Reference source not found.** 22:
1. TFRs created and disseminated by the traffic manager responsible for TMFs regarding predicted vertiport and corridor capacities.
2. Decision making by the traffic manager responsible for TMFs (with automation support) to approve the contingency plan for a flight regarding alternate landing sites should arrivals at the intended destination be stopped.
3. Decision-making by dispatcher/flight planner and RPIC to proceed to launch the flight.
4. Aircraft performance (capacity to divert to an alternate landing site).
5. Actual weather development.
6. Actual capacities of vertiports or other landing sites.

In Scenario 1, the assumed failure mode is that the traffic manager responsible for TMFs, with support from weather forecasting software and potentially with support from a meteorology service, sets the TFRs specifying the Vertiport Arrival Rates too high relative to uncertainty regarding the potential for convective weather to either reduce or stop arrivals at several vertiports. This is Potential Failure Mode 1.1, named "TFR: Overestimation of Vertiport Capacity," as shown in the FMEA analysis for strategic deconfliction in Figure 21.

As a result, when aircraft begin to arrive at the vertiports, a significant number are forced to divert. Because the TFRs set the arrival rates too high relative to this convective weather event, there are not enough alternative vertiports or other landing pads available to handle all the diverting aircraft. As a result, the emergency backup sites must be utilized to allow a number of these aircraft to land at reserve sites.

This emergency backup plan is analogous to operational planning in the military for air missions to identify pre-coordinated rally points for air (helicopters) and ground forces [Smith, 2021]. This requires a plan for coordination and communication among all the relevant entities. Figure 24 indicates the nature of such coordination for potential Air Force operations. For UAM operations, this would include coordination and communication involving the RPICs for the involved aircraft, their associated dispatchers (if any), the traffic manager responsible for TMFs, the PSU(s), local law enforcement, and, if necessary, ATC.
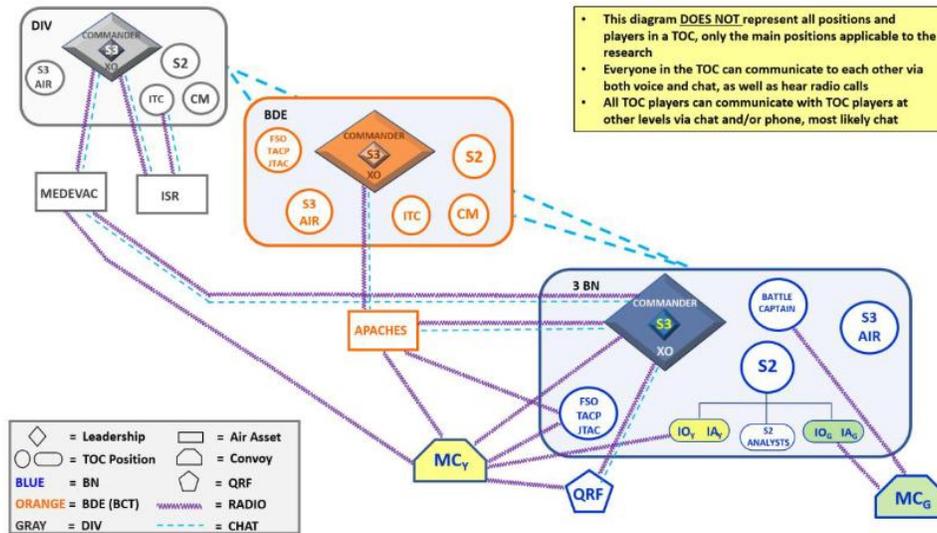
Figure 24. Coordination and communication among units for an Air Force mission.

For the military, this pre-planning further includes the identification of rally points for air (helicopter) and ground forces, such as sports fields and parks (see R1-R4 in Figure 25). The same could apply to the design of a UAM operation. Such rally points or emergency reserve landing areas could be considered in the design and approval of the contingency plan for a flight.
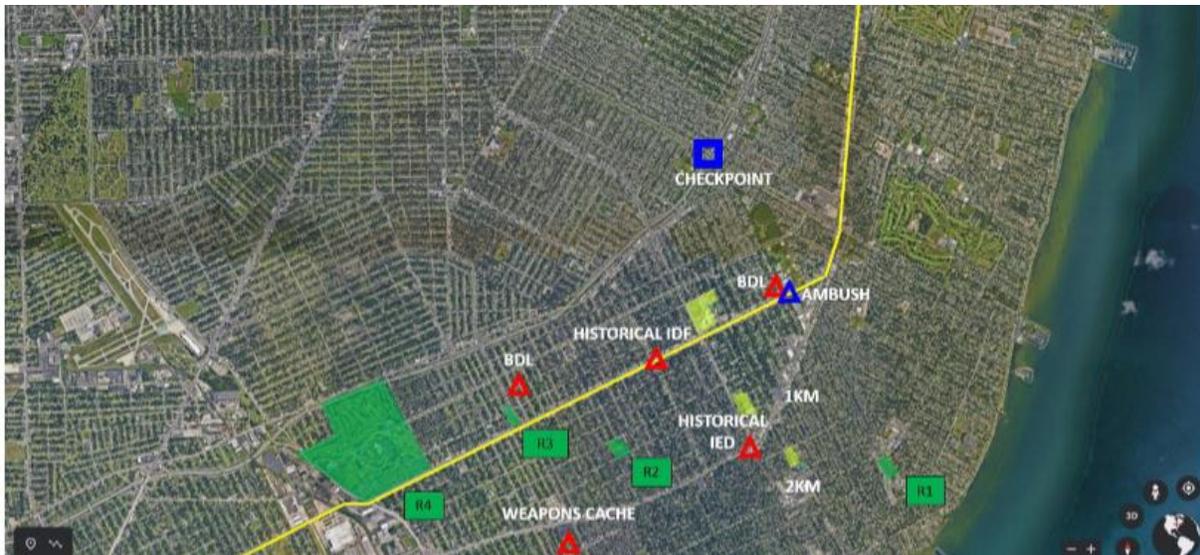
Figure 25. Pre-planned rally points as part of a contingency plan.

As long as sufficient landing areas have been identified in the UAM planning and in the specific contingency plans for the involved UAS, the result is a safe but inefficient UAM operation. In addition, because the RPICs have control of the UAS, the traffic manager responsible for TMFs could coordinate to have aircraft land at any vertiports or landing pads that, although they are not identified as alternates in the contingency plans for aircraft, could still be utilized for those aircraft that have sufficient energy reserves to reach them. (If a large number of aircraft require alternative landing sites, software to support the traffic manager responsible for TMFs in making such alternate airport assignments and approving the 4D trajectories to get there would be useful.)

Such coordination is viable because there is an RPIC in control of each UAS who can make the adjustments to the trajectory and landing site for the aircraft based on instructions from the traffic manager responsible for TMFs.

In addition, if necessary, the emergency reserve landing sites specified in the contingency plans can be used. However, if the reserve landing sites are not adequately cleared of pedestrians or objects, the operation could result in injuries or damage to property. (The likelihood of this latter possibility could be further reduced if the aircraft had vision systems to help ensure landing in a cleared area. It should also include an announcement system to notify pedestrians to clear the area, as well as coordination with local law enforcement.)

This preplanning is importantly different from current FAR 121 operations, in which the dispatcher develops a contingency plan for diversion of a particular flight if there is predicted weather that could impact landing at the planned destination (for example, specifying and fueling for a specific alternate airport as part of the flight release). For UAM operations, because there are fewer possible suitable sites for diversion as compared with 121 operations, approval of diversion plans for specific flights will have to be obtained preflight centrally by the traffic manager responsible for TMFs.

Figure 26 provides an FMEA assessment of the risk associated with such a scenario (see the line highlighted in gray). The following notation is used in the figure:

1. SEV: How severe is the effect?
2. OCC: How frequently is the cause likely to occur?
3. DET: How probable is the detection of the mode or cause?
4. RPN: Risk Priority Number (RPN = SEV x OCC x DET)

A Risk Priority Number (RPN) of 18 indicates that, given the assumed CONOPS for UAM operations, there is a risk that merits investigation to determine suitable mitigations.

This analysis serves to highlight an important point. While completing such an FMEA analysis feels straightforward, assumptions are hidden within the analysis. For example, in specifying the OCC (i.e., "How frequent is the cause likely to occur?"), it feels reasonable to ask the related question: "How frequently could the generation of a TFR that overestimates the capacities of vertiports lead to an emergency landing?"

For this sample analysis, the thought process is that overestimation will happen occasionally and, when this happens, there is a small but not negligible likelihood that the following may occur: *i)* a diversion will be required; *ii)* the planned alternate landing sites will be unavailable; and *iii)* the emergency landing site selected by the RPIC in consultation with the traffic manager responsible for TMFs and dispatcher/flight planner might not be as safe as desired. This reasoning leads to a SEV (severity) of 9.

In short, this exercise suggests caution regarding the completion of an FMEA: it may incorporate hidden assumptions, making the resultant numbers less than fully informative. However, if the impact of the FMEA is to trigger a more detailed assessment of that possible failure mode to identify mitigation, this may appropriately lead to the evaluation of mitigations.

Process Step/Input or Design Item	Potential Failure Mode	Potential Enablers/Contributors	Potential Effect(s) of Failure	S E V	Potential Cause(s) / Mechanism(s) of Failure	O C C	Current Process Controls to Prevent Failure Mode	Current Process Controls to Detect Failure Mode	D E T	R P N	Recommended Actions	Person/Org Responsible for Actions
1. Strategic deconfliction	TFR: Overestimation of vertiport capacity	Lack of suitable alternative landing site	Inadequate estimation of vertiport capacity resulting in the need for diversion of an aircraft. If the contingency plan to handle such a diversion is inadequate, then an emergency landing may be required	9	Inaccurate weather forecast; inadequately trained and experienced traffic manager and vertiport operator; lack of access to trained meteorologist	2	See Attachment X	See Attachment X	1	18	See Attachment X	TMF; Dispatch; RPIC; Vertiport
1. Strategic deconfliction	TFR: Underestimation of vertiport capacity		Unnecessary delays; reduced throughput		Inaccurate weather forecast; inadequately trained and experienced traffic manager and vertiport operator; lack of access to trained meteorologist							
1. Strategic deconfliction	TFR: Overestimation of airspace (corridor) capacity	Lack of suitable alternative trajectory; high demand for airspace	Inadequate safety eval. of proposed 4D trajectory for a flight		Inaccurate weather forecast; inadequately trained and experienced traffic manager; lack of access to trained meteorologist; brittleness of strategic deconfliction software							
1. Strategic deconfliction	TFR: Underestimation of airspace (corridor) capacity		Unnecessary delays; reduced throughput;		Inaccurate weather forecast; inadequately trained and experienced traffic manager; lack of access to trained meteorologist; brittleness of strategic deconfliction software							
1. Strategic deconfliction	Inadequate evaluation of airspace restrictions	Inadequate tactical replanning	Inadequate safety eval. of proposed 4D trajectory for a flight		Inaccurate weather forecast; inadequately trained and experienced traffic manager; brittleness of strategic deconfliction software							
1. Strategic deconfliction	Incorrect assumptions about obstructions		Inadequate safety eval. of proposed 4D trajectory for a flight		Iinadequately trained and experienced traffic manager; brittleness of strategic deconfliction software; out of date data on obstructions							
1. Strategic deconfliction	Incorrect assumptions regarding trajectories and contingency plans for other previously approved and upcoming flights	High demand for airspace and/or vertiports	Inadequate safety eval. of proposed 4D trajectory for a flight		Inadequately trained and experienced traffic manager; brittleness of strategic deconfliction software							
1. Strategic deconfliction	Inadequate assumptions about performance capabilities of new flight and all other potentially interacting flights (including DAA capabilities)		Inadequate safety eval. of proposed 4D trajectory for a flight		Inadequately trained and experienced traffic manager; brittleness of strategic deconfliction software; inadequate data input from flight operator regarding aircraft and automation capabilities							
1. Strategic deconfliction	IInadequate potential trajectory conflict evaluation (DAA) algorithm	High volume and complexity in airspace usage	Inadequate safety eval. of proposed 4D trajectory for a flight		Brittleness of DAA algorithm(s); inadequate data input from flight operator regarding aircraft and automation capabilities							
1. Strategic deconfliction	Inadequate safety evaluation of proposed 4D trajectory for a flight	High volume and complexity in airspace and vertiport usage	Inadequate safety eval. of proposed 4D trajectory for a flight		Inadequately trained and experienced traffic manager; brittleness of strategic deconfliction software; brittleness in DAA algorithm(s) inadequate data input from flight operator regarding aircraft and automation capabilities							

Figure 26. FMEA analysis for Potential Failure Mode: TFR: Overestimation of vertiport capacity.

Description of Potential Failure Stories for the System: Scenario 2. Suppose we want to consider an extension of Scenario 1 by asking the question: "What other factors shown in the ID could interact with the occurrence of a TFR that overestimates TFR capacity?". Review of the nodes in the ID in Figure 22 leads to the conclusion that the occurrence of this failure mode in combination with a loss of communications could result in a significant safety concern. This second scenario is driven by such a variation of Scenario 1, which was generated from the FMEA analysis focused on the reliance of strategic deconfliction on the specification of TFRs (see Figure 21).

The additional factor added in Scenario 2, after reviewing the factors identified in the influence diagram, is an interaction with another subsystem indicated in the influence diagram: communications. Namely, assume that there is a complete loss of communication for an aircraft planning to land at a vertiport that has been stopped because of convective weather. Note that a more challenging variation on this scenario would arise if several aircraft operated by a particular flight operator lost communications or if the entire UAM airspace lost communications.

In this scenario, the RPIC can no longer communicate with the UAS. Thus, the UAS must operate autonomously. Consideration of the ID in Figure 22 indicates that a number of factors interact to determine the likelihood of such a scenario and the safety of the outcome:

1. Accuracy of the weather prediction as information to consider in determining vertiport capacities.

2. Skill of the weather forecaster and performance of supporting weather forecasting software.
3. Skill of the traffic manager and supporting software in generating TFRs for the vertiports.
4. Skill of the dispatchers and RPICs at judging the weather forecast in developing flight plans and associated contingency plans, as well as in making go/no-go decisions just prior to departure.
5. Effectiveness of the traffic manager responsible for TMFs and deconfliction software in determining TFRs as input to the strategic deconfliction decisions.
6. Effectiveness of the strategic deconfliction software.
7. Performance of RPICs, dispatchers, the traffic manager responsible for TMFs, and local law enforcement in managing diversions.
8. Effectiveness of FAA or Community-Based Rules (regulations) in specifying minimum energy reserves and requirements for strategic deconfliction to ensure adequate alternative landing sites (including emergency reserve sites), as well as associated procedures for making safe use of these sites.

Figure 27 shows a notional layout of a UAM system. V1-V5 are vertiports that can each serve several UAS. The two unlabeled boxes are landing sites for a single UAS at a hospital and a business. R1-R4 are emergency reserve landing sites (at sports fields and parks). The corridors are not shown, but they connect all the landing sites.
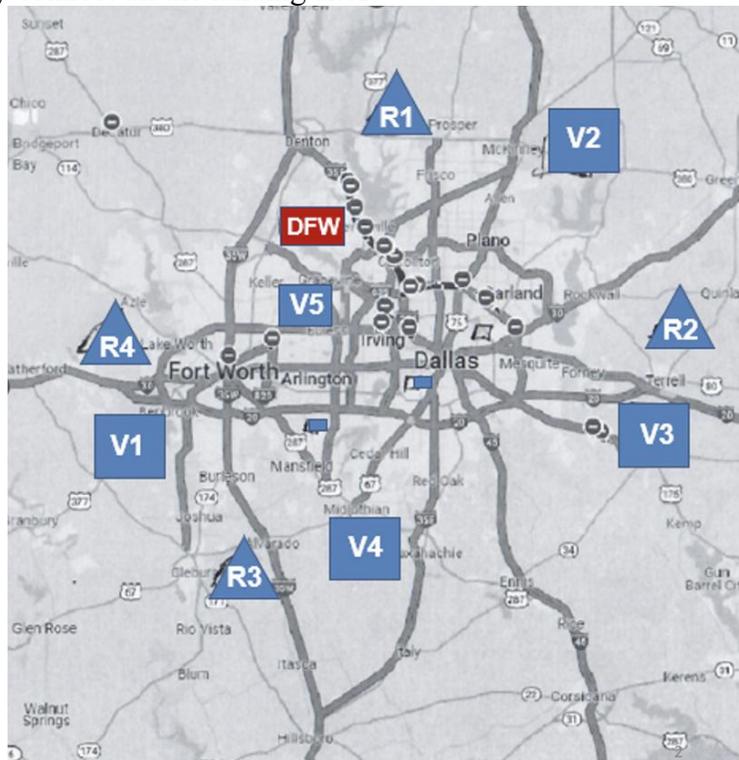

Figure 27. Notional layout of UAM system.

For Scenario 2, assume the following steps occur:
1. The weather forecast (TFM Convective Forecast) predicts sparse coverage of the entire UAM airspace (25-39%) for the next four hours.

2. The traffic manager responsible for TMFs for this urban area consults with a meteorologist and all of the vertiport operators and sets TFRs for each of the vertiports at 75% of maximum capacity. This assumes that any vertiport stoppages due to air mass thunderstorms may be randomly distributed across V1-V5 and R1-R3 over time.
3. A dispatcher considers the weather forecast and the TFRs and consults with a meteorologist. With concurrence of the RPIC, the dispatcher submits a proposed 4D trajectory and contingency plan for Flight XYZ, with a departure from V1 and a destination of V2. The contingency plan indicates V3 as the alternate vertiport and R1 as the planned emergency landing site if necessary. These decisions are based on the experience of the meteorologist, dispatcher, and RPIC, which indicates that if V2 arrivals are stopped due to convective weather, V3, V4, and R1 are unlikely to also all be impacted by storm cells at the same time. The dispatcher also sends any flight data for this aircraft necessary for the strategic deconfliction software under the control of the traffic manager responsible for TMFs to evaluate potential concerns regarding spacing relative to the DAA capabilities of all of the relevant aircraft.
4. The strategic deconfliction software used by the traffic manager responsible for TMFs evaluates the proposed 4D trajectory, taking into consideration the TFRs and the already approved flights during this time period (including their proposed 4D trajectories and their contingency plans). The traffic manager responsible for TMFs is monitoring the approved trajectory and, if necessary, can override the approval. In this case, the trajectory and contingency plan for Flight XYZ is approved by the software and is not overridden by the traffic manager.
5. As part of the preflight inspection, just prior to OFF, the dispatcher and RPIC evaluate the weather and conclude that the flight plan is safe.
6. The flight departs.
7. As the flight approaches V2, arrivals at V2, V3 and R1 are stopped due to thunderstorm activity.
8. Before the RPIC can coordinate with the traffic manager responsible for TMFs regarding a feasible alternative vertiport instead of V3 or V4 and send instructions to the UAS, one aircraft goes NORDO, losing both primary and secondary communications.
9. The automation takes over full control.
10. A visual signal is displayed to the aircraft as it arrives in the vicinity of V2, indicating that V2, V3, and R1 arrivals are stopped.
11. Based on this visual signal, the automation diverts to the secondary alternative vertiport, V4.
12. The traffic manager responsible for TMFs coordinates with the RPICs of the other airborne aircraft to ensure that Flight XYZ has a clear route as it proceeds.
13. The automation proceeds to fly Flight XYZ to the selected landing site, and it lands autonomously but safely. To enable this, the vertiport operator has coordinated with the other diversions to V4 to allow the NORDO flight to land first.

This scenario raises a number of questions that need to be addressed, including the determination of whether considerations associated with Factors 1-8 above will be effectively managed. It also indicates a number of questions in terms of whether Steps 1-13 are the best design and whether each of these steps can be performed effectively. Of particular importance are the following questions:

1. Is Scenario 2 sufficiently likely to require addressing the mitigations necessary to support the steps listed above (or some alternative set of steps)?
2. How will the aircraft automation be informed regarding the stopping of landings at V2, V3, and R1? (Note: if this signal could also indicate a new diversion site in circumstances where the contingency plan is inadequate, this would add additional safety.)
3. What if the weather won't allow the NORDO aircraft to approach V2? How is this detected, and how should the aircraft automation respond?
4. How will coordination be managed by the automation if an aircraft without air-to-ground communication needs to land at one of the emergency reserve sites?
5. What should regulations specify in terms of reserve energy and the range of alternatives indicated in a contingency plan?

Note that, methodologically, these two scenarios suggest that a thorough SRA should employ standard SRA methods, as described earlier, and then be supplemented with a test plan for evaluating a specified set of critical scenarios. The generation of these scenarios could be enhanced through the use of an ID to provide a shared visual representation for use by SMEs to consider possible critical interactions more completely among factors that could result in a significant safety risk. This is analogous to the requirement to use Critical Task Analysis Reports for guidance in the design and evaluation of FAA software (see page B-7 of FAA HFEQ).

Integrated Use of IDs and FMEA. The above discussion indicates how IDs can be used to provide a structured method to identify potential interactions among the different factors that influence the safety of a UAM operation. There are two assumptions that merit discussion:

Assumption #1: The ID can Facilitate Collaboration among Multiple SMEs. The first assumption is that such a shared visual representation can more effectively support collaboration by multiple SMEs to produce a more complete and accurate representation, indicating the risk factors and the interactions that need to be considered in completing an SRA. Essentially, the methodology is to work with SMEs to generate the ID, and includes the following factors:

1. A draft ID is prepared by a single SME or a focus group with several SMEs collaborating.
2. This draft is sent to other SMEs with an appropriate range of expertise to address the following questions:
   a. Question 1: Should any high-level nodes be added, deleted, relabeled, or broken up into more than one separate node to produce an updated ID?
   b. Question 2: Should subcategories be produced showing underlying factors influencing one or more of the high-level nodes in the updated ID?

First, regarding actual vertiport performances, the factors identified in an initial draft by Ohio State University (OSU) SMEs included: *i)* actual weather; *ii)* forecast weather; *iii)* available landing and parking pads; *iv)* available staff; *v)* training and experience of traffic management staff; *vi)* training and experience of weather support staff; and *vii)* cybersecurity. The additional factors identified by University of North Dakota (UND) SMEs include: *i)* the capability of vertipads to meet aircraft requirements (*i.e.*, compliance with standards such as required size of concrete and the load-bearing capability of the pad); *ii)* night operations capabilities; *iii)* wake turbulence and ability to adapt for landing; and *iv)* automation support.

Second, regarding actual flight operator performance, the factors identified in the initial draft by OSU SMEs included: *i)* staffing levels; and *ii)* procedures. The additional factors identified by Embry-Riddle Aeronautical University (ERAU), Kansas State University (KSU), and UND SMEs included: *i)* training and experience of flight operator staff (RPICs, dispatchers, and meteorologists); and *ii)* automation support.

Third, regarding DAA, the factors identified in the initial draft by OSU SMEs included: *i)* staffing levels; *ii)* procedures; *iii)* cybersecurity; and *iv)* separation requirements. The additional factors identified by ERAU, KSU, and UND SMEs included: *i)* training and experience of flight operator staff (RPICs, dispatchers and meteorologists); *ii)* presence of wildlife (such as birds or other items not 'seen' by DAA system); *iii)* hardware performance; *iv)* software performance; *v)* weather impacts on DAA performance (fog and clouds); *vi)* presence of low altitude obstacles that may impact maneuvers (i.e., buildings and powerlines restrict where you can move).

Fourth, regarding power and propulsion, the factors identified by ERAU, KSU, and UND SMEs included: *i)* reliability of propulsion system; *ii)* control system failures impacting effectiveness; *iii)* redundancy of propulsion systems; *iv)* icing effect on propulsion systems; *v)* maintenance; *vi)* qualifications to repair various propulsion systems.

Note that the above analysis is for illustration purposes only. A more complete analysis would require the participation of a greater range of SMEs.

Assumption #2: The ID can be used to Systematically Identify Factors that Affect Safety. The second assumption is that the updated ID can be used to systematically ask the question: What factors could interact to affect safety? This can be accomplished by selecting one of the failure modes identified by the FMEA and reviewing each of the nodes and sub-hazards identified in the influence diagram, asking the question: Could this factor shown in the ID have an impact on the likelihood of occurrence of a failure mode or the severity of its consequences? If so, it may need to be incorporated into the critical scenarios included in the test plan for scenario-based safety assessment.

The two scenarios described earlier illustrate this very clearly, with the identification of a number of factors identified in the ID that could affect the impact of the failure mode "TFR: Overestimation of Vertiport Capacity" on safety. An extreme example in terms of a system design challenge was the interaction in Scenario 2 of an overestimation of vertiport capacity (due to an unexpected stopping of arrivals due to weather at the intended destination and two of the landing sites that were planned as contingencies for a flight) with a loss of communication by a UAS planning to land at that vertiport, resulting in a significant increase in risk.

Process Controls to Prevent Failure Mode. The traffic manager responsible for TMFs is responsible for developing a TFR indicating the predicted capacity for a vertiport for some time period, based in part on weather forecasts. The dispatcher and RPIC are responsible for considering this when deciding whether to launch a flight. If the failure mode arises, the RPIC can coordinate with the traffic manager responsible for TMFs to determine the landing site to use for a diversion due to the closure of a vertiport.

Recommended Actions: a much more integrated process for coordination needs to be defined and supported by automation -

1. Preflight, the flight operator needs to submit its contingency plan for diversions.
2. Preflight, the strategic deconfliction automation used by the traffic manager responsible for TMFs needs to consider the contingency plans for all of the proposed and active flights and determine whether sufficient capacity has been reserved to ensure safe diversion landing sites for all aircraft.
3. The traffic manager responsible for TMFs, dispatchers/flight planners, RPICs, ATC, and local law enforcement need to be trained on a procedure to manage a flight that needs to divert.
4. The automation needs to support the traffic manager responsible for TMFs in determining safe diversion sites for aircraft that cannot land at their planned vertiports and in ensuring that the 4D trajectory for diversions is conflict-free.

8.1.7.3 Autonomous Command and Control (C2).

The third application of qualitative risk assessment to UAM applies the STPA hazard analysis framework to the autonomous C2 system in a UAM setting.

8.1.8.3.1 System Analysis.

The intention of system analysis is to understand the system as a whole, including all components, interactions, and functions, with a focus on its structure and behavior. Figure 28 shows a block diagram illustrating the interactions between the different components in the normal operation of autonomous C2. The Flight Control Processor (FCP) will receive data from the Communication modules from the Ground Control Systems. That data will then be analyzed and processed via the FCP and passed to the Emergency Management System to adjust the movement of the UAS.
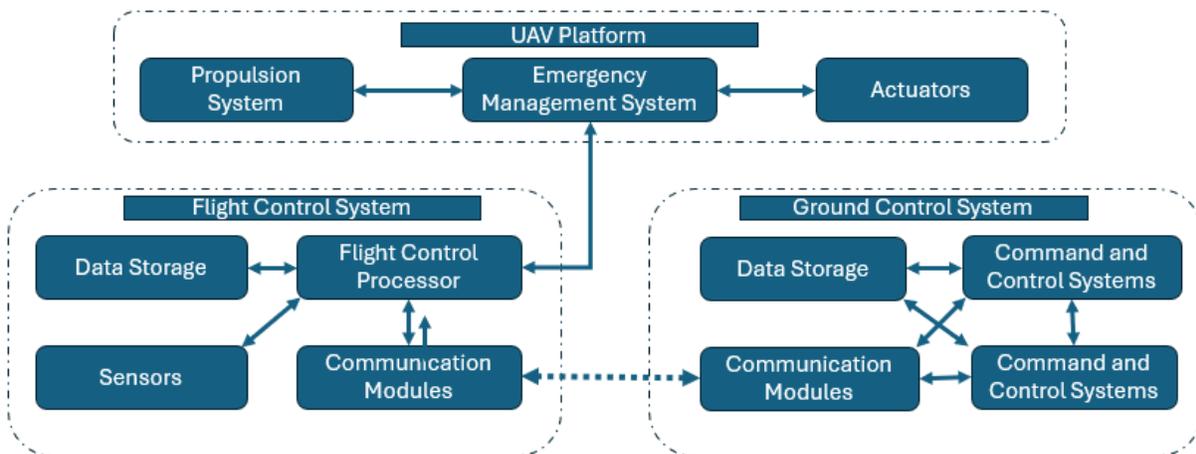
Figure 28. STPA applied to command and control (C2): System components and interactions.

8.1.8.3.2 Identifying Constraints.

The next step is determining the necessary safety constraints for the system to operate without leading to an accident. These are rules or conditions to maintain safety. The constraints were identified through the following five (5) step process:

1. Step 1: Root Causes - List potential root causes of failures and potential contributing factors.
2. Step 2: System Interactions - Describe the system's interactions with other systems.
3. Step 3: Environmental Factors - Describe relevant environmental factors for this system.
4. Step 4: Subsystems - Decompose the system into subsystems.
5. Step 5: Failure Scenarios - Describe potential failure stories (scenarios) for the system.

Step 1: Root Causes. Three primary safety constraints have been identified for autonomous C2:

1. In case of primary channel failure, the UAM system must maintain a continuous and secure communication link with ATC, with automatic failover to backup channels.
2. All critical components of the UAM system must have operational redundancy to ensure continuous functionality under failure conditions.
3. The system must perform real-time operational monitoring with automated diagnostics to detect and alert to deviations from standard operating parameters.

Step 2: System Interactions. Autonomous C2 interacts with and relies upon network reliability constraints in the following three (3) ways:

1. The communication network must maintain at least two independent communication channels to ensure redundancy.
2. Network protocols must dynamically adjust based on real-time data analysis to safely optimize performance and reliability.
3. In case of primary channel failure, the communication system must automatically switch to a backup channel within a predefined time frame.

The likelihood of the system operating within the safety constraints will be improved through the use of the following three (3) best practices:
1. Use data analytics to predict and address potential network failures before they occur. By analyzing trends and patterns in network performance data, maintenance can be scheduled proactively, reducing the risk of unexpected failures.
2. Implement real-time monitoring systems to detect and respond to network issues instantly. This allows for immediate corrective actions, minimizing the impact of any network disruptions.
3. Incorporate multiple layers of security within the communication networks to protect against cyber threats, ensuring that the data used for safety protocols is available, secure, and reliable.

In addition, designing the UAM system with the following three (3) trajectory control and deconfliction constraints will also improve the likelihood of operating under safety constraints:
1. The system must continuously monitor and adjust flight trajectories to avoid conflicts, with a minimum separation distance maintained at all times.
2. Conflict detection algorithms must identify potential trajectory conflicts and initiate resolution procedures automatically and in real time.
3. Trajectory adjustments in response to detected conflicts must be executed within a specific time frame to ensure timely deconfliction.

Step 3: Environmental Factors. The following two (2) environmental factors directly impact the safe operation of autonomous C2:

1. Signal strength and reliability.
2. Weather conditions.

Regarding signal strength and reliability, the following three (3) best practices will mitigate the impact of low or unreliable signal strength on the safe operation of the autonomous C2 system:
1. Implement protocols for regular testing and validation of signal strength and quality.
2. Ensure multiple communication channels to provide backup in case of failure.
3. Establish protocols to identify and mitigate potential sources of signal interference.

Regarding weather conditions, the following three (3) best practices will mitigate the impact of inclement or uncertain weather on the safe operation of the autonomous C2 system:
1. Integrate advanced weather monitoring sensors and systems for real-time updates.
2. Develop protocols for adaptive responses to changing weather conditions, including automatic route adjustments.
3. Implement procedures for handling severe weather scenarios, including system shutdowns or rerouting to safe locations.

Step 4: Subsystems. There are two relevant subsystems for autonomous C2:

1. Communication channel encryption: All communication within the autonomous C2 system must utilize robust encryption protocols to prevent unauthorized access, which are regularly updated to address emerging security threats.
2. Redundant communication channels: The system must maintain multiple independent communication channels to guarantee connectivity at all times, even if one channel fails.

Step 5: Failure Scenarios

Two failure scenarios of autonomous C2 have been identified as examples:
1. Failure due to communications loss and/or delay.
2. Failure due to cyber-attack.

The first failure scenario will occur under the following two situations:
1. First, there is either i) a lack of timely response over the communications channel or ii) inappropriate maneuvers in response to communication loss.
2. Second, there is an overreliance on automated systems without adequate fail-safes for communication breakdowns.

To reduce the likelihood and/or severity of the first failure scenario, it is recommended that the following components and procedures be included in the design:
1. In case of communication loss, the UAM system must initiate an immediate response protocol to manage the vehicle, avoiding inappropriate maneuvers safely.
2. The UAM system must maintain multiple, independent communication channels to ensure continuous connectivity, even if one channel fails.

The first failure scenario will occur under the following two situations:

1. First, there is a failure to detect and respond to the cyber-intrusion in a timely manner.
2. Second, either incorrect or malicious commands are being followed by the UAM vehicles due to the system being compromised.

To reduce the likelihood and/or severity of the second failure scenario, it is recommended that the following components and procedures be included in the design:
1. The autonomous C2 system must incorporate advanced cyber-intrusion detection mechanisms that continuously monitor for and immediately flag any unauthorized access or anomalies.
2. UAM vehicles must be equipped with an autonomous fail-safe operational mode that activates in case of compromised C2 system control, ensuring safe operation or landing.

Hierarchical Safety Control Structure. The block diagram in Figure 29 has been redesigned to include redundant backup communication systems, onboard C2 systems, a cyber-intrusion detection system, and an automated fail-safe landing system.
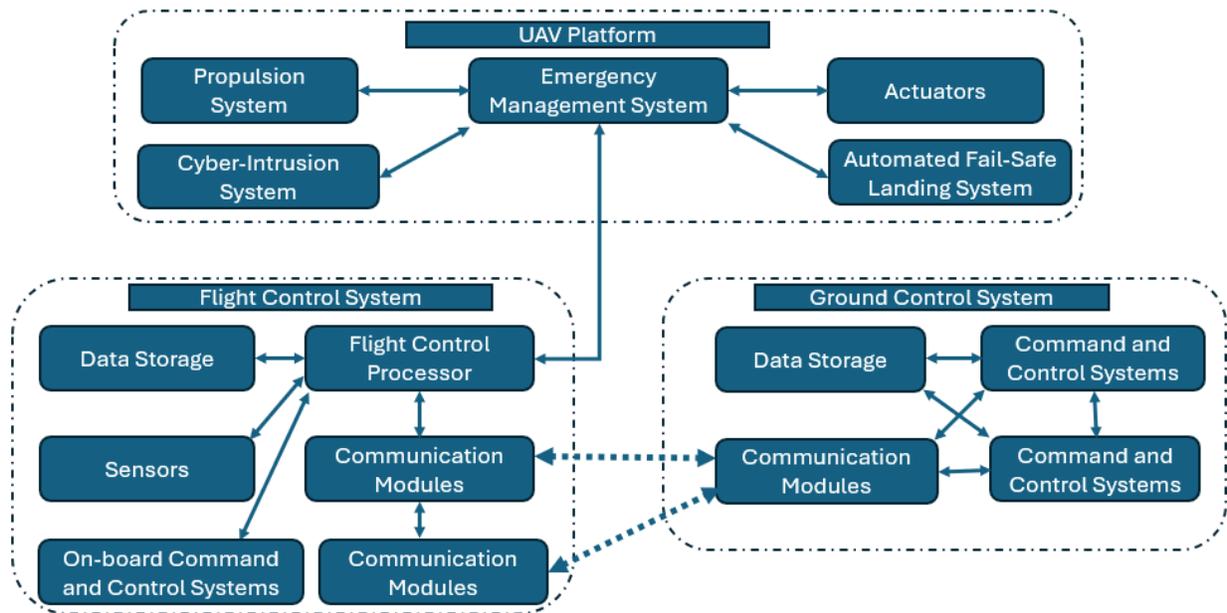
Figure 29. STPA applied to command and control (C2): augmented system diagram.

8.1.8.3.3 Accident Analysis.

The first failure scenario involved a communication failure where the communication channels between UAM vehicles and ground control systems experience a malfunction or total failure, leading to a possible airspace conflict. To mitigate the risk of a communication failure, redundant communication models were implemented into the UAM flight control system to ensure constant communication with ground control stations. Additionally, an on-board C2 system should be implemented into the onboard flight control system to provide real-time automated command and control, given a ground communication fault. These two systems should mitigate the risks associated with the first failure scenario.

The second failure scenario involved a cyber-attack where the C2 systems are compromised due to a malicious cyber intrusion. Two new mitigations were put into the block diagram to prevent cyber-attacks on the UAM. The first is a cyber-intrusion system that detects cyber anomalous behaviors and sends alerts to the pilot in command and flight controllers. The second system would be an automated fail-safe landing system for a UAM compromise. The automated system would take over all craft functions and land it at the nearest, safe location to prevent malicious behaviors toward the UAM.

8.1.7.4 Human-Automation Interaction and Human-Human Interaction.

The fourth and final application of qualitative risk analysis to UAM applies the STPA hazard analysis framework to human-automation and human-human interaction in a UAM setting.

8.1.7.4.1 System Analysis.

The intention of system analysis is to understand the system as a whole, including all components, interactions, and functions, with a focus on its structure and behavior. Figure 30 shows a block diagram illustrating human-automation interactions in the normal operation of a UAM system. Conceptually, the automation portion of human-automation interaction can be broken down into a control system, navigation system, and human interface with the control system. The human operator at the ground control will interact with the command-and-control system. The communication modules will then relay the data to the UAS platform. In the event of a communications malfunction (and possible additional non-normal events), the human passenger could have an interface on the UAS platform for the human-automation interaction with the control system for manual control. Naturally, there is difficulty in designing this interface for non-expert human passengers to maximize the likelihood of a low-severity outcome.
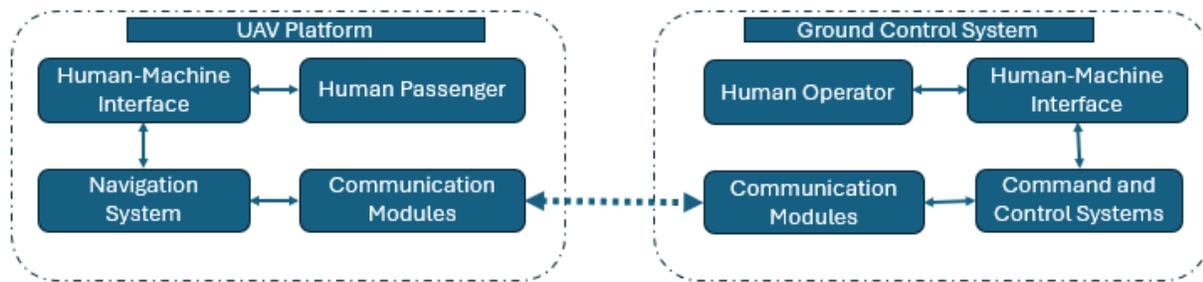
Figure 30. STPA applied to human automation: system components and interactions.

Identifying Constraints.

The next step is determining the necessary safety constraints for the system to operate without leading to an accident. These are rules or conditions to maintain safety. The constraints were identified through the following five (5) step process:

1. Step 1: Root Causes - List potential root causes of failures and potential contributing factors.
2. Step 2: System Interactions - Describe the interactions of the system with other systems.
3. Step 3: Environmental Factors - Describe relevant environmental factors for this system.
4. Step 4: Subsystems - Decompose the system into subsystems.

5. Step 5: Failure Scenarios - Describe potential failure stories (scenarios) for the system.

Step 1. Root Causes. Four primary safety constraints have been identified:
1. Systems must be designed to facilitate intuitive and efficient interaction between the human operator and the automation, enabling seamless transitions between automated and manual control.
2. Autonomous systems must provide operators with clear and understandable feedback regarding their decision-making processes and current operational status to support informed human oversight.
3. Operators of semi-autonomous systems must receive comprehensive training and regular skill updates to manage and intervene in automated operations effectively.
4. Systems must support effective communication and collaboration among human operators in control centers, facilitating coordinated responses to emergencies or system failures.

Step 2. System Interactions. Four safety constraints specific to the interaction have been identified.

1. The UAM system must provide comprehensive fail-safes and override capabilities that allow human pilots to take immediate and full manual control in case of automation failure or unforeseen circumstances.
2. The UAM system must incorporate advanced collision avoidance and situational awareness technologies to assist human passengers and ensure safe operation during manual control.
3. The UAM system must maintain continuous, transparent communication with human supervisors, alerting them to system status and potential issues and allowing for timely human intervention when needed.
4. The UAM system must implement stringent cybersecurity measures to protect against hacking, unauthorized access, and other cyber threats at all automation levels.

Step 3. Environmental Factors. The following two (2) environmental factors directly impact the safe operation of human-automation interaction:

1. Emergencies and critical weather conditions.
2. Unique and/or distinct geographical features.

Regarding the environmental factor of emergencies and critical weather conditions, the following safety protocol for human interaction with autonomous systems is recommended:
1. Emergency Override Systems: Ensure that human operators can quickly and effectively take control of the autonomous system in an emergency.
2. Advanced Weather Prediction and Response Systems: Integrate advanced weather prediction technologies to anticipate and respond to critical weather conditions.
3. Training in Emergency Procedures: Provide comprehensive training to human operators in handling emergencies and operating in critical weather conditions.
4. User Interface Design for Emergency Situations: Design user interfaces that present critical information and options during emergencies, allowing quick and informed decision-making.

Regarding the environmental factor of unique and/or distinct geographical features, the following safety protocol for human interaction with autonomous systems is recommended:

1. Incorporate detailed geographical data into the system to assist operators in understanding the unique challenges of different locations.
2. Develop protocols that allow operators to customize their decision-making processes based on local conditions and requirements.
3. Provide specialized training for operators in managing UAM systems in different geographical locations, focusing on unique challenges and requirements.

Step 4: Subsystems. There are two relevant subsystems for human-automation interaction:

1. Control and navigation system.
2. Non-normal condition response system.

Regarding the control and navigation system, the following safety constraints on the design are recommended:

1. The control system must be designed with redundancy to ensure continuous operation even in the event of a component failure. It must incorporate real-time diagnostic capabilities to detect and address faults promptly.
2. The navigation system must integrate multimodal sensors (e.g., GPS, radar, and light detection and ranging) to ensure accurate positioning and routing and must be capable of functioning under various environmental conditions, including those that may disrupt standard GPS signals.
3. The human-interface system must be intuitively designed to facilitate easy and effective interaction between the operator and the system, providing clear, concise, and timely information to support decision-making, especially in emergencies.

Regarding the non-normal condition response system, the following safety constraints on the design are recommended:

1. In the event of a non-normal condition, the system must allow human operators to quickly and efficiently take control, overriding automated functions if necessary.
2. The system must provide comprehensive and understandable information to the human operator regarding the nature of the non-normal condition and the status of automated functions, facilitating informed decision-making.
3. Human operators must be thoroughly trained to handle non-normal conditions, including simulations of various scenarios, to ensure preparedness for real-world emergencies.
4. The system must be resilient to a range of non-normal conditions, including cyber-attacks, system malfunctions, and environmental challenges, and must have protocols in place to safely manage these situations with or without human intervention.

Step 5: Failure Scenarios. Four failure scenarios of human-automation interaction have been identified:

1. Communication issues.
2. Weather, environment, and geography neglect.
3. Vulnerability to GPS/ADS-B jamming and spoofing.
4. Autopilot mismanagement in aviation.

First, semi-autonomous operations are vulnerable to failure when communication channel considerations are not incorporated sufficiently well into the navigation and traffic systems. To reduce the likelihood and/or severity of the first failure scenario, it is recommended that the system have multiple, independent communication channels to ensure continuous and reliable connectivity, enabling manual override at all times.

Second, semi-autonomous operations are vulnerable to failure when weather, environment, and geography are not adequately incorporated into navigation and traffic systems. To reduce the likelihood and/or severity of the second failure scenario, it is recommended that navigation and traffic alerting systems integrate real-time environmental and geographical data to adjust operational parameters accordingly.

Third, semi-autonomous operations are vulnerable to failure when there is over-reliance on GPS and ADS-B without the benefit of a backup navigation system; this is because of the vulnerability of GPS and ADS-B to jamming and spoofing. To reduce the likelihood and/or severity of the third failure scenario, it is recommended that navigation systems be designed to include countermeasures against GPS/ADS-B jamming and spoofing, ensuring alternative navigation capabilities.

Fourth, semi-autonomous operations are vulnerable to failure when incorrect input in autopilot altitude settings occurs. To reduce the likelihood and/or severity of the fourth failure scenario, it is recommended that pilots receive comprehensive training on autopilot systems and adhere to strict verification procedures for all autopilot settings.

Hierarchical Safety Control Structure. The block diagram in Figure 30 has been redesigned to include redundant backup communication systems, onboard C2 systems, a cyber-intrusion detection system, and an automated fail-safe landing system, as shown in Figure 31.
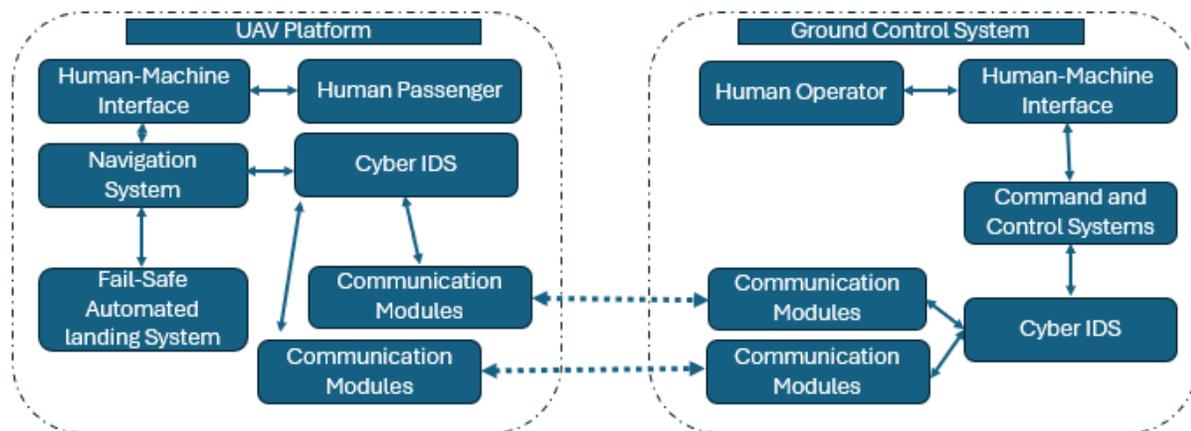

Figure 31. STPA applied to human automation: augmented system diagram.

8.1.7.4.2 Accident Analysis.

One of the human-interaction failure scenarios outlined autopilot mismanagement, where the PIC activates the autopilot system but inadvertently selects an incorrect altitude setting. Training and

communication constraints were identified to mitigate the risk of autopilot mismanagement. This training should facilitate effective communication and collaboration among PICs at operation centers. In addition, redundant checks from a primary and secondary operator could be implemented to ensure all settings are correct for each flight. The additional training should mitigate the risks associated with this failure scenario. The automation could also monitor for an implausible or unusual altitude setting.

Another of the human-interaction scenarios highlighted pilots misinterpreting instructions. Like the previous scenario, training programs should be implemented to mitigate this risk. The fail-safe automated landing system has also been added to the block diagram to autonomously land the UAS platform if it operates in non-normal conditions. The additional training and automated system should mitigate the risk of this failure scenario.

8.2 Quantitative Assessment of Risk for UAM Operations

As noted earlier, while quantitative risk assessment methodologies may yield impactful insights, possibly even more impactful than those obtained by qualitative risk assessment, they are inherently reliant upon data availability for input. As data for UAM systems is not widely available, or at least not publicly available, as is natural for a nascent technology, this scarcity limits their applicability to UAM. That said, it is possible to leverage quantitative risk assessment methodologies in the absence of data by *i)* considering a specific (but representative) CONOPs, *ii)* obtaining the required numeric inputs from a SME, and iii) performing a sensitivity analysis to determine how sensitive the overall risk assessment is to the SME provided values.

To illustrate this, the analysis in the Task 3 report applies decision analysis to a specific UAM CONOPS focused on flight scheduling and strategic deconfliction due to uncertain adverse weather, where the specific probabilities of the relevant events have been estimated by a SME with expertise in airline meteorology.

8.2.1 Selective Review of Quantitative Risk Assessment Methodologies.

Decision Analysis, (*e.g.*, [Muenning, 2017], [Parnell, 2013], [Raiffa, 1968]), abbreviated as DA, is a well-established technique in which the sequence of uncertain outcomes leading to an event of interest is laid out as a tree (*i.e.*, a mathematical graph without loops), typically from a starting state or condition on the left (the root of the tree) and ending in any one of the possible end states or conditions on the right (the leaves of the tree). All vertices (including the root) except for the leaves represent an uncertain event in that one of multiple states will result, due to either the evolution of the system state or due to a relevant environmental factor.

This tree, as described thus far, effectively enumerates possible final states that may plausibly result from the initial state. But this enumeration is only the first part of the decision tree; the critical second part is to enumerate the conditional probabilities at each decision vertex. More precisely, for any such vertex, say v, hereafter called the parent, it will branch out to a set of child vertices, say $(v_1,...,v_k)$, and the directed edges, say $(e_1,...,e_k)$, connecting the parent with its children will be labeled with the conditional probability of the state evolving from the parent to each child. These labels, *say $(l_1,...,l_k)$*, are nonnegative numbers that sum to one (*1*), i.e., the labels represent a

(conditional) probability distribution for the evolution of the system conditioned on being at the parent.

For any leaf (end state), the (conditional) probability of ending on that leaf is obtained by multiplying the (conditional) probabilities on the edges forming the (unique) path from the root to the leaf. Naturally, adding up the (conditional) probabilities of all possible leaves yields one, so that the collection of edge (conditional) probabilities in the tree induce a probability distribution on the leaves. It is often the case that the leaves may be aggregated, say into desirable vs. undesirable events, and the probability of a desirable vs. undesirable end state is obtained by summing the (conditional) probabilities over the leaves in each event.

The advantage of a decision tree is its specification of all possible end states and (more importantly) the probability distribution on those states, but this advantage is only possible due to the (often, in practice, large) number of edge (conditional) probabilities needed to specify the tree. This specification requirement is the primary disadvantage of decision trees because knowledge, or even a feasible means of estimation, of these (conditional) probabilities is unavailable.

A critical design aspect of decision trees is parsimony, in the sense that the goal of any model is to provide a sufficient level of detail to capture the dynamics of interest, but any additional detail should be cut. In the context of decision trees, this parsimony is reflected in the choice of all possible children for each parent vertex. That is, in practice, the enumeration of all possible next states that might result from a parent vertex depends critically on what types of system dynamics and exogenous factors are considered sufficiently plausible for inclusion in the model.

In the specific application of decision trees for safety, the issue of parsimony is particularly fraught on account of the intention of the model is to capture, or even uncover, hazardous states that may give rise to accidents. That is, a parsimonious safety model may be self-defeating in that if attention is only given to normal operations, then all non-normal states that might result in an accident are omitted. On the other hand, a non-parsimonious model, say an extravagant model, may be impractical on account of the difficulty in estimating (conditional) probabilities of rare events.

8.2.2 Application of Specific Quantitative Risk Assessment Methodologies to UAM Systems. This section extends the work presented earlier, which leveraged two qualitative risk assessment methodologies (ID and FMEA) in the context of flight planning and strategic deconfliction of UAM. In particular, it applies Decision Trees (DT) to a scenario, denoted Scenario 3 and described below, which is a variation of Scenario 1.

Scenario 3 Specification. Recall, the largest source of uncertainty regarding the likelihood of a significant safety risk in Scenario 1 is the adequacy of the weather forecast and the translation of such a forecast into TFRs. On the plus side, the timeframes for such forecasts for UAM operations are much shorter than those involved in traditional FAR Part 121, 135, and 91 operations. On the challenging side, the sensors and weather prediction models are currently much more limited for UAM operations than they are for higher altitude flights.

Scenario 3 was developed during knowledge elicitation with a meteorologist with over 19 years of experience with aviation weather forecasting for an airline. Figure 32 provides the outline of the

scenario presented to this SME. The Vs are vertiports; the Rs are pre-planned emergency landing sites, such as parks; and the unlabeled blue boxes are landing pads for individual aircraft at urban sites, such as hospitals or businesses.
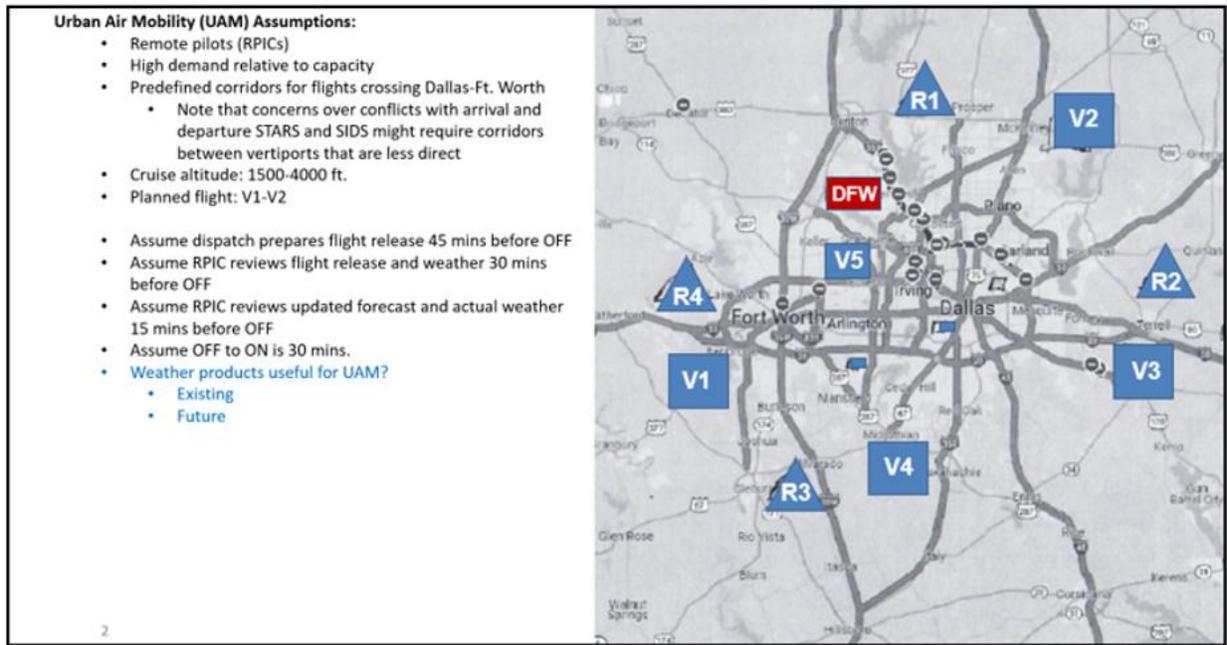
Figure 32. Description of Scenario 3.

As part of the presentation of this slide, the SME was asked about relevant weather information and provided the following input:

1. "You would need sensors that provide information on a number of variables, such as winds, ceilings, visibility, temperature, barometric pressure, radar, and lightning detection. This includes actual and forecast weather."
2. "Since this is a small area, you would need sensors that provide adequate data."
3. "The meteorologist would want high-resolution weather models to provide forecasts for short time frames, and the ability to manually input parameters when necessary."

Figure 33 indicates the flight corridors and provides an example from a military operations order of pre-planned emergency landing sites. It also indicates that the focus of Scenario 3 involves a flight from V1-V2 at 2100Z in July.

Figure 33. Flight corridors for Scenario 3.

It should be noted that, although this corridor design was used for discussion, the SME indicated there could be significant issues with these corridors crossing arrival and departure gates. This could necessitate a different layout for the corridors, along with a possible need at times for coordination with ATC.

The SME indicated that the details of the scenario are very important (such as location, time of day, time of year, and specifics of the weather forecast). For example, he indicated that if the scenario were at 23Z, the likelihood of a thunderstorm developing and closing V2 would be much lower than at 2100Z.

This has major implications for SRAs: Aggregation of probabilities over large time frames, locations, and conditions is not very informative relative to evaluating the safety risks involved with a particular UAM operation.

To create an example, the meteorologist suggested showing a frontal system or trough over Denton, TX, moving southwest at 40 kts (see **Error! Reference source not found.** 34):
1. "If a frontal system was coming through over Denton, or even a trough, then I can time it out and plan. With this example, it is likely it will close landing sites at some points."
2. "If it's moving at 40 kts., the pilot should usually be fine to depart from V1 and land at V2."
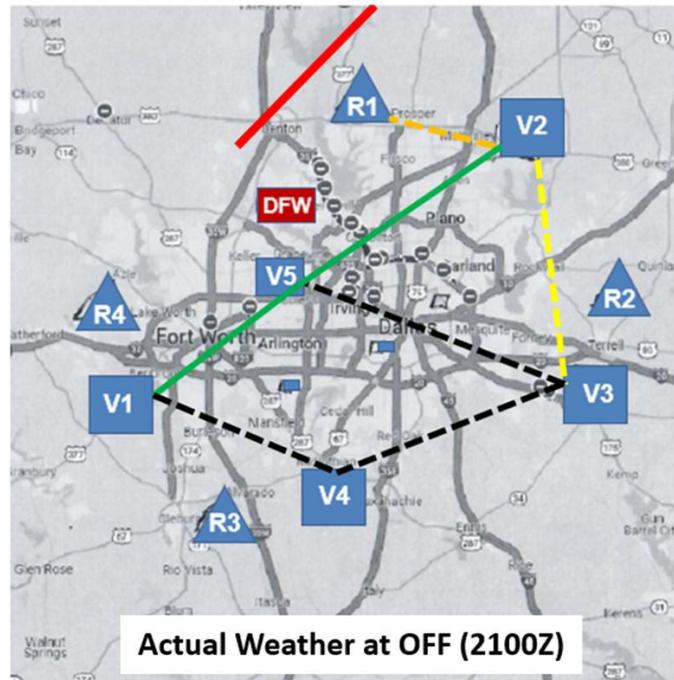
Figure 34. Scenario 3 with a frontal system or trough over Denton at 2100Z.

As illustrated earlier, the use of FMEA includes a structured process for subjective estimation of the likelihood and severity of the outcomes associated with the different failure modes that have been identified [ASQ].

As an extension of this method, DTs could be used for specific critical scenarios to support a quantitative analysis for a safety risk assessment.

Scenario-Based Evaluation of Risks. The fundamental concept illustrated here is that, to support effective evaluation of the risk associated with a proposed UAM operation, a test plan should be developed that specifies a representative set of concrete scenarios that covers all of the important different *classes* of situations that need to be safely handled by a proposed operation. In this test set, each such class is defined generically and then illustrated by a concrete exemplar to help the evaluators more fully and effectively assess risks and potential mitigations.

It should be noted that a number of the scenarios in this test set likely apply to UAM operations for any urban area. The test set, therefore, does not need to be re-developed from scratch when a proposal for operations at a new UAM site is considered. There will likely be a few additional classes of scenarios that need to be added to capture unique considerations associated with any given urban area, but this generalization of the test set across different UAM sites helps make this approach more feasible.

For the example below, the generic class focuses on ensuring safe UAM operations for scenarios where a frontal system is impacting the capacity of vertiports. To help in the evaluation of the safety of a proposed operation in such a scenario, a concrete illustration using a flight in the Dallas-Fort Worth (DFW) area is developed.

The fundamental hypothesis is that such a scenario-based evaluation of risks based on consideration of the risks and potential mitigations associated with concrete scenarios will help the evaluators of a proposed UAM operation to more fully and accurately complete their assessment.

The process illustrated below involves several steps:
1. Use the results of an FMEA analysis to identify a critical failure mode as a starting point. Then use an influence diagram to identify the factors that need to be incorporated into an illustrative scenario that captures the important interactions and cascading of actions, events, and environmental conditions interacting with that failure mode and impacting the associated risk.
2. Define the scope of the class of scenarios that this scenario is intended to represent. For this example, the failure mode used is the development of a TFR that overestimates the capacity of vertiports. The particular cause discussed in this scenario is the development of a convective weather system.
3. Specify the details of a concrete, illustrative scenario to characterize this class of scenarios.
4. Develop a DT that captures the important decisions and events characterizing this scenario, as well as the outcomes.
5. Estimate the probabilities associated with chance nodes in this decision tree. To provide a sensitivity analysis, this could include estimates of confidence intervals for these probabilities instead of just point estimates. These estimates could be based on subjective probabilities provided by SMEs or historical data if available.
6. Estimate the probability of occurrence of the possible outcomes associated with this specific scenario.

The evaluator can then use this analysis to inform an assessment of the risk associated with this particular scenario and of the broader class of scenarios that it represents. This includes:
1. Characterize the severity of the potential consequences associated with each path through the DT, using a decision matrix such as the one shown in Figure 35.
2. Consider the estimated probabilities of the different paths and the severity of the associated consequences to produce an assessment of the risk associated with each path through the DT.

If certain paths are judged to have excessive risk, specify the mitigations necessary to reduce that risk to an acceptable level so that a proposed flight operation can be approved.

This process does not attempt to fully quantify risk. Rather, it is intended to improve the judgment of an evaluator by providing a structured framework indicating contributing factors along with quantification of the likelihood of certain outcomes to support an evaluation.

>7: Extreme risk
– detailed treatment plan required
6,7: High risk
– needs senior management attention and treatment plan as appropriate
4,5: Medium risk
– manager level attention and monitoring as appropriate
<4: Low risk
– manage by local level procedures

→ Consequence →

	Insignificant / Injuries etc.					
People	Injuries or ailments not requiring medical treatment.	Minor injury or First Aid Treatment Case.	Serious injury causing hospitalisation or multiple medical treatment cases.	Life threatening injury or multiple serious injuries causing hospitalisation.	Multiple life threatening injuries. Less than 10 fatalities.	Multiple fatalities, 10 or more
Reputation	Internal Review	Scrutiny required by internal committees or internal audit to prevent escalation.	Scrutiny required by external committees or Auditor General's Office, etc.	Intense public, political and media scrutiny. Eg: inquest, front page headlines, TV, etc.	Government inquiry or Commission of inquiry or adverse national media in excess of 1 week.	Government inquiry and ongoing adverse international exposure
Organisational / Client impact	Small delay, internal inconvenience only.	May threaten an element of the service delivery function. Business objective delayed. Easily remedied, some impact on external stakeholders.	Considerable remedial action required with disruption to a Group for period up to 1 month. Some business objectives not achieved.	Significant loss of critical information. Disruption to one or more Groups for up to 3 months. Some major objectives not achieved.	Permanent loss of critical information, substantial disruption to CASA or external intervention for over 3 months. Threatens existence of a Group within CASA. Major objectives not achieved	Threatens ongoing existence of CASA.

	Numerical	Historical
↑	>1 in 10	Is expected to occur in most circumstances
	1 in 10 – 100	Will probably occur
Probability	1 in 100 – 1000	Might occur at some time in the future
	1 in 1000 – 10000	Could occur but considered unlikely or doubtful
	1 in 10000 - 100000	May occur in exceptional circumstances
↑	< 1 in 100000	Could only occur under specific conditions and extraordinary circumstances

		Insignificant 0	Minor 1	Moderate 2	Major 3	Severe 4	Catastrophic 5
Almost Certain	(5)	5	6	7	8	9	10
Likely	(4)	4	5	6	7	8	9
Possible	(3)	3	4	5	6	7	8
Unlikely	(2)	2	3	4	5	6	7
Rare	(1)	1	2	3	4	5	6
Extremely Rare	(0)	0	1	2	3	4	5

Figure 35. Sample decision matrix from ASSURE A21 Final Report (from Smith 2022).

Incorporation of Subjective Probabilities into a DT. For quantitative support of a risk assessment, the combination of FMEA analyses and IDs can help to generate and describe critical scenarios such as Scenario 3. For each such scenario, a decision tree can then be developed to assess risk.

Figure 36 shows an illustrative decision tree for Scenario 3. For this sample analysis, it is assumed that the traffic manager responsible for TMFs consults with a meteorologist and decides to assign a TFR restricting each of the vertiports and emergency reserve areas to 75% of their full capacity to ensure the availability of landing slots if diversions are necessary. It is further assumed that, during the pre-flight evaluation just before OFF, the RPIC decides that the weather is favorable and the flight departs.
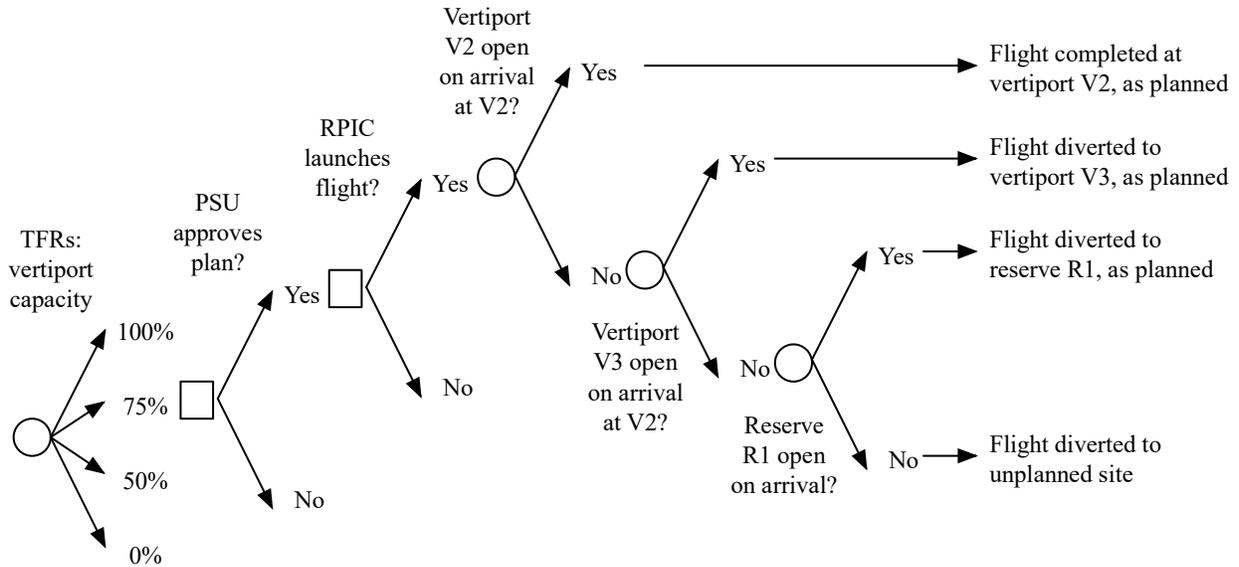
Figure 36. Decision tree for Scenario 3.

The DT in Figure 36 indicates that three major decisions are made in this scenario: *i)* creating TFRs (which don't have to be the same for all of the vertiports and could also be focused on corridor airspace segments); *ii)* approval of the proposed flight plan and associated contingency plan by the traffic manager responsible for TMIs based on consideration of all of the flights relevant to this timeframe; and *iii)* a final decision by the RPIC to proceed with the flight shortly before departure). There are also three chance nodes associated with the impact of the actual weather development on the availability of V2, V3, and R1 for landing this flight.

Error! Reference source not found. 37 shows the subjective probability estimates relevant to this DT provided by the expert meteorologist. **Error! Reference source not found.** 38 then shows the aggregation of these event probabilities to estimate the probability of different scenario variations (paths) associated with the decision tree.
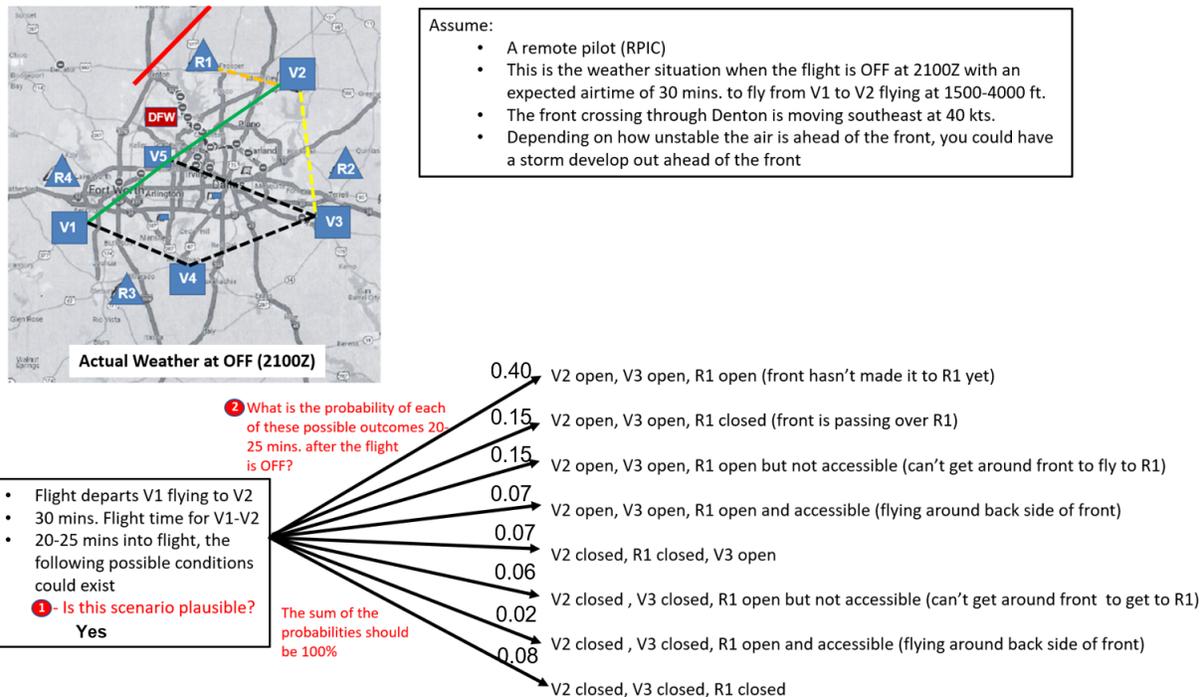
Figure 37. Subjective probability estimates provided by meteorologist.

Other input from meteorologists included:
1. "You're going to have to think about whether some of these routes could be crossing through arrival or departure lanes for DFW."
2. "Here are my answers to your questions, but please remember that there are so many variables that could affect these answers."
3. "This is a very realistic scenario."
4. "If possible, the dispatcher should probably have planned and fueled to have V5 and maybe even V4 available as feasible alternates, and made R1 the least desirable alternate. But that begins to add extra fuel requirements. And they'll also be required to have a certain amount of reserve fuel in addition to having enough to make it to all of these alternates."
5. "You'd like to have the meteorologist monitoring and in close contact with the dispatcher."
6. *"The traffic manager responsible for TMFs needs access to meteorology expertise as well."*
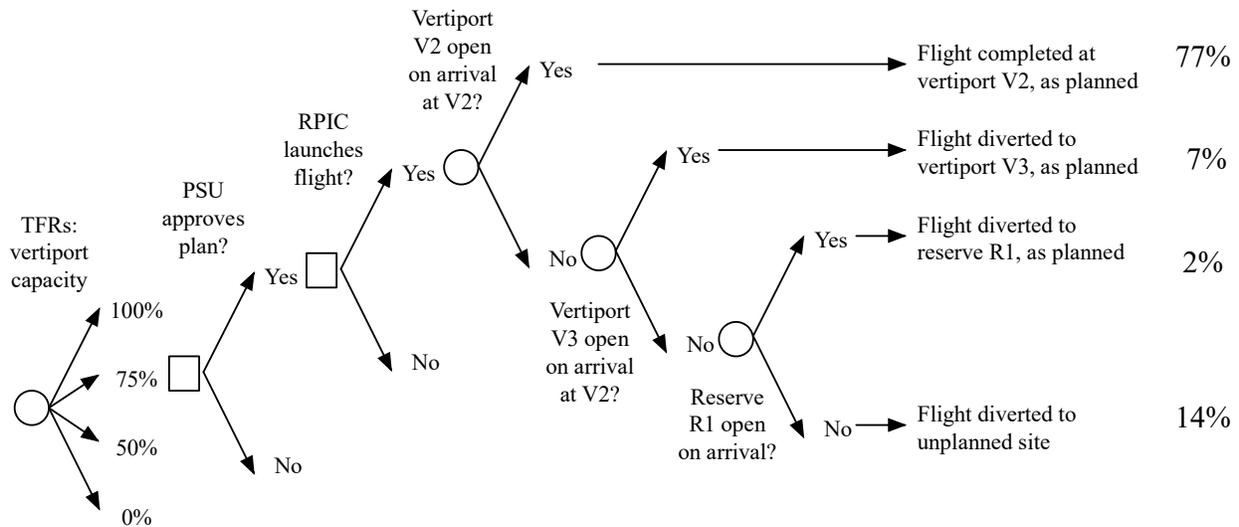
Figure 38. Decision tree for Scenario 3 with probabilities on each leaf.

As additional input, the meteorologist (who has had a great deal of experience observing the decision-making of airline dispatchers and pilots in Part 121 operations) provided estimates of the probability of a pilot deciding to proceed with the flight in this scenario (see **Error! Reference source not found.** 39).

Figure 39. Estimates of the probability of a pilot deciding to proceed with the flight.

Reviewing this scenario, an evaluator could conclude that:

1. This is a plausible, likely scenario for the proposed urban area. This conclusion might be further supported by an analysis of historical weather data or further input from expert meteorologists.
2. Without additional specified mitigations, if this scenario occurs, the performance of the flight described in this example is not sufficiently safe. If launched, it is likely (with an estimated conditional probability of 14%) that, given this scenario, the flight will have to attempt an emergency landing at an unplanned site (such as a sports park or on a highway), with the potential for minor or moderate consequences (injury to passengers or pedestrians and a negative impact on the perception of the safety of such flight operations, having an major impact on the achievement of business objectives).
3. Without additional specified mitigations, performance of the proposed operation is categorized as high risk. Thus, without additional specified mitigations, the proposed flight operation should not be approved based on this scenario.

In summary, the Scenario Based Evaluation process described above defines a six (6) step process. For each scenario in the test set:

1. Judge whether, in the proposed urban area, a given scenario from the test set is likely.

2. Determine the possible outcomes (paths in the DT) if this scenario occurs in the proposed urban area.
3. Estimate the probability of each outcome (paths in the DT) in the proposed urban area, conditional on the occurrence of this scenario.
4. Characterize the consequences associated with each outcome (path in the DT) in the proposed urban area.
5. Categorize the risk associated with this scenario using a risk matrix like the one shown in Figure 35 based on the (conditional) probabilities of the different outcomes (paths in the DT) and the associated consequences.
6. If any one of the scenarios in the test set that is judged to be likely in the proposed urban area has an assigned risk based on the matrix in Figure 35 that is established as high or extreme, then the proposed flight operation should be rejected unless sufficient mitigations are added as part of the proposed flight operation and documented in the request for approval.

In this example, the conditional probability of the path in the DT with arrivals to V2, V3, and R1 stopped has been estimated as almost certain (14%) for this scenario. If that outcome occurs, the consequence can be categorized as potentially minor or moderate, as the contingency plan indicated that V2, V3, and R1 were the only available planned alternates for this flight. Using the decision matrix shown in **Error! Reference source not found.** 35, performance in this scenario would be categorized as high risk. The requested approval of this flight operation would therefore be rejected unless mitigations were introduced and documented in a revised request for approval.

8.2.3 Mitigations to Reduce Risk.
The following five (5) mitigations will reduce risk and increase approval of the proposed flight operation:
1. Ensure Defined Procedures and Adequate Training.
2. Pre-Flight Evaluation of Contingency Plans by the Traffic Manager Responsible for TMFs.
3. Flight Operator Pre-Flight Contingency Planning.
4. Real-Time Traffic Management.
5. Broad Mitigations.

Ensure Defined Procedures and Adequate Training. The first mitigation is to require defined procedures and adequate training of all the involved personnel to ensure effective coordination and communication among them if an ad hoc emergency landing or a landing at one of the designed emergency landing sites is necessary (keeping in mind the possibility that this could involve coordination to land more than just this one UAS at a particular site).

Pre-Flight Evaluation of Contingency Plans by the Traffic Manager Responsible for TMFs. The second mitigation is pre-flight evaluation of the contingency plan for each proposed flight by the traffic manager responsible for the TMF relative to the already approved plans for other flights to ensure that there are enough landing slots available at the available vertiports to deal with potential off-nominal weather scenarios that result in diversions.

This assessment could be made easier if the number of potential landing slots constructed at the vertiports is large relative to possible demand. If demand is expected to be high relative to capacity,

however, the flight operator would need to demonstrate that there will be a qualified traffic manager responsible for the TMF and for evaluating each flight who will, with automation support, determine whether the proposed 4D trajectory and associated contingency plan for alternative landing sites for a given flight is feasible given the already approved plans for other flights. Note that this approval would likely be an automatic assessment (using the TFRs) and approval/disapproval for each proposed flight by the technology, based on constraints specified by the traffic manager.

To support this function of the traffic manager responsible for the TMF, that individual would be responsible for the specification of TFRs defining ground delay programs to limit the number of slots at each vertiport planned to be filled by approved flights if there are no diversions. This information would need to be disseminated to the flight operators to inform their flight planning. (Ground stops for arrivals at a given vertiport could also be used for more tactical traffic flow management.)

To evaluate proposed flight plans, the traffic manager would then have to provide the supporting automation with input specifying the possible scenarios that need to be accommodated. For example, based on an ensemble weather forecast, for Scenario 3, the traffic manager might specify that the set of approved 4D trajectories and contingency plans for Scenario 3 has to be viable if landings at V2, V3, and R1 are stopped from 2120-2230Z. This type of judgment would require the expertise of a meteorologist (or a traffic manager with sufficient meteorology training). And this information would have to be disseminated to the flight operators as well to inform their flight planning.

The automation could then consider the active TFRs to determine whether a particular proposed flight plan and its associated contingency plan should be approved (with oversight by the traffic manager responsible for the TMF). (If the flight operator submitted a range of acceptable arrival times along with a preference for a flight's estimated time of arrival, then the automation could use this flexibility in its consideration for approval of the proposed flight plan.)

The need to conduct such contingency planning implies a requirement to demonstrate adequate staffing and training of traffic managers responsible for the TMF and meteorologists, as well as for the design of procedures and supporting automation.
The implication is that, for a proposed flight operation to be approved, the above mitigations would have to be demonstrated as part of the proposal.

Flight Operator Pre-Flight Contingency Planning. A further implication of this scenario is that, to get approval for the proposed flight operation, the dispatcher/flight planner (which, for smaller operations, could be the RPIC) would be trained and capable of using this information from the traffic manager responsible for the TMF to generate a proposed 4D trajectory and contingency plan specifying feasible alternative landing sites for each flight. Note that such pre-flight planning would likely occur 45-60 minutes before planned OFF and would require automation support.

In the example presented for Scenario 3 above, the specified contingency plan indicated that V3 and R1 were the only alternates that this flight could use. If the traffic manager responsible for the TMF has indicated that contingency plans must deal with the possibility that V2, V3, and R1 could

all be closed from 2120-2230Z, then this submitted flight plan with its contingency plan would be rejected by the traffic manager responsible for the TMF. As long as it has been specified that the traffic manager responsible for the TMF has the responsibility and capability to make such a judgment, the proposal by the flight operator could be approved as this check by the traffic manager responsible for the TMF would provide the necessary safeguard when the flight operator submitted a proposed flight plan that was not acceptable from a system safety perspective.

Given this process, the flight operator could consider the information from the traffic manager responsible for the TMF when developing the contingency plan for the flight in Scenario 3, and either:

1. Submit as contingencies V3, V5, and R1 if the aircraft could be fueled to use those sites as alternates (but could not divert to V4), as the traffic manager responsible for the TMF has not indicated that V5 might be stopped for arrivals in this scenario. This would then be a viable contingency plan that the traffic manager responsible for the TMF could approve if there weren't too many other diversions to V5 relative to its capacity, with a 75% reduction in arrivals due to the ground delay program.
2. Submit a flight plan that indicates an estimated time of departure at 2230Z, indicating V3 and R1 as the alternates because it could not be fueled to divert to V5.

Real-Time Traffic Management. The fourth mitigation, i.e., real-time traffic management, involves the following:

1. Shortly before the estimated time of departure, the process submitted for approval would have to indicate that a qualified RPIC (potentially with input from a qualified meteorologist) would review the current weather and make the final go/no-go decision based on the weather development shortly before departure.
2. The submission would also need to indicate that, as the flight proceeded, the RPIC and meteorologist would monitor the weather to see if an early diversion decision should be made. In Scenario 3, for instance, the meteorologist might inform the RPIC of the need to divert to V5 15 minutes into the flight. Because of the limited availability of landing slots, however, this would need to be coordinated with the traffic manager responsible for the TMF (with supporting software). (The meteorology SME who was consulted commented that the RPIC would want to have the meteorologist "looking over his shoulder" during this flight.)
3. The submission for approval of this flight operation would further have to indicate that if, as an example, the traffic manager responsible for the TMF (with input from his supporting meteorologist and the V2 and V3 vertiport managers) stopped arrivals into V2 and V3 20-25 minutes into the flight discussed in Scenario 3, the traffic manager responsible for the TMF (with automation support) would have to consider the approved contingency plans for all of the flights filed to arrive at V2 and V3 in this time period and assign and communicate diversion airports to the RPICs of the airborne aircraft based on consideration of the number of available slots at V4 and V5. A ground stop would also have to be initiated for flights filed to arrive at V2 and V3 if they had not yet departed.
4. The automation used for traffic flow management (with oversight by the traffic manager responsible for the TMF) is assumed to have responsibility for approving the 4D trajectory for a flight. The trajectories for the diversions would need to be checked in real time as part of the assignment of diversion vertiports to particular flights, or the structure of the corridor

airspace would have to be designed appropriately, with separate lanes for each direction along a corridor and ideally with passing lanes and/or reliance on DAA for safe separation. Note that this includes an assumption that, in the real-time planning of the diversions, flights have sufficiently conflict-free 4D trajectories to their diversion vertiports and have been planned to arrive at different times for landing at their vertiports, or that automation is capable of sequencing flights for landing as they arrive at the diversion vertiports.

Note that this latter mitigation (Point 4) may be the most challenging mitigation to implement and would require careful thought regarding the necessary ground-based support automation (for the Traffic Manager responsible for the TMFs and staff at vertiports) and/or necessary on-board support automation.

Broad Mitigations. Finally, in terms of the challenges of defining an acceptably safe process to support Scenario 3, some broad mitigations could be considered:
1. Ensure that the available vertiports have a landing capacity that is significantly higher than the potential demand in off-nominal scenarios so that contingency planning is much easier.
2. Limit operations to short flight durations to reduce the need to plan for unexpected weather.
3. Design corridors with unidirectional lanes that allow passing.
4. Require a pilot on board for flights to reduce the potential consequences associated with emergency landings for missions with potentially high consequences (such as flights with passengers on board or flights over areas with a high density of pedestrians).

In summary, the discussion above illustrates the benefit of evaluating the approval of a proposed flight operation based on the consideration of concrete scenarios, as this helps the evaluator by increasing the perspicuity of important considerations.

8.2.4 Further Consideration of Scenario 2.

Scenario 2 added factor: Loss of air-ground communication as a flight approaches its destination in a scenario where convective weather stops arrivals to one or more vertiports. To evaluate the extent to which this scenario needs to be considered in determining the approval of a proposed flight operation, two questions arise. First, how likely is this to occur? Is loss of communication going to be rare enough that it can simply be ignored? Second, if it does arise, what mitigations are necessary to make it safe?

The likelihood of a loss of communication depends strongly on the details regarding the design of the communication capabilities, including backup systems. That capability is likely to improve significantly by the time remotely piloted UAM vehicles become routine, so a thorough analysis was not attempted.

However, an expert in aviation communications was asked to provide a qualitative assessment of the likelihood of a communication outage for a single aircraft to emphasize the importance of looking at interacting factors such as a closure of vertiports simultaneously with a loss of air-ground communication using the envisioned communication network as described earlier in the CONOPS for Scenarios 1-3. The response of the SME to the following questions is provided below.

Question: Assume loss of air-ground communication by a single remotely piloted UAM aircraft. How could this communications system fail? How likely are such failures?

1. Mechanical failure, such as an antenna. SME response: "Low likelihood. There are well-tested products available that could be used for UAM application. The newly integrated systems may have a slightly higher risk associated with failure while operational limits are being pushed in dense environments."

2. Software failure/bug. SME response: "Moderate likelihood. Software failures are less likely than bugs. However, due to constant software updates, some systems can be more vulnerable to operational errors (e.g., an operator uploading source code without robust testing, causing the failure). As the new UAM networks begin to converge into the NAS, constant software updates may be required based on demands, which could increase the likelihood of this failure."

3. Cyberattack? SME response: "Moderate to high likelihood. As UAM becomes increasingly integrated into the NAS, it will create more and more attack vectors. This could increase the likelihood of advanced persistent threat actors targeting the systems. The actors could aim for espionage, data theft, or system disruptions."

4. Other? SME response: "The other points of failure would revolve around environmental concerns. First, Weather conditions could disrupt communications. This would be a low to moderate likelihood, but very dependent on the geographical location. Second, solar flares could disrupt satellite communications. This would be a low to moderate likelihood based on the solar maximum."

These qualitative estimates suggest that a scenario involving the closure of a vertiport, along with a loss of air-ground communication, needs to be addressed in the evaluation of a proposed flight operation. One mitigation is obviously to improve the design of the hardware and software to reduce the likelihood of such a communications failure relative to these estimates. However, this input from the SME suggests that additional mitigations need to be in place, assuming this kind of scenario could arise.

8.3 Risk Assessments for UAM Operations - Summary.
In this section, methods for both qualitative and quantitative risk assessments have been reviewed. Examples of their application to UAM have then been provided. The examples not only illustrate how these methods can be applied, however. Based on the results, they highlight some important system design decisions that need to be carefully considered to ensure safety in terms of the assignment of roles and responsibilities, the development of procedures, and the design of safety automation.

9.0 CONCLUSION

9.1 Research Needs to Address Gaps

The detailed recommendations presented in the body of this report indicate significant gaps for several areas defining the research necessary to inform the design and use of automation to support safe UAM operations. These are summarized below in terms of:

- Separation assurance.
    - DAA.
    - Return to mission.

- o DAA for autonomous control by aircraft.
- o Traffic flow management.
- Effective design of digital infrastructure for vertiports.
- Weather decision making.
- Communication.
- Risk Assessment.

Additional detail is available in the Phase 1 report regarding the relevant literature, in the Phase 2 report regarding approaches to risk assessment, and in the Phase 3 report on the design and use of supporting automation technologies as well as relevant standards, regulatory processes, and policies.

9.1.1 Separation Assurance. These detailed recommendations can be organized into the following research categories, as there are a number of complementary areas where research is needed to guide the design and use of automation to ensure safe separation assurance for UAM. This includes consideration of automation to support DAA, return to mission and traffic flow management, as well as consideration of the design of the airspace environment within which these technologies need to perform. These are identified individually below.

9.1.1.1 DAA
   a. *Terminal-Specific Well-Clear Definition & Separation Assurance.* Current well-clear definitions are calibrated for enroute operations. In terminal corridors and vertiport approach flows (secs. 4.1, 4.1.2, 5.2), using enroute spacing creates excessive nuisance alerts or over-conservatism that reduces throughput.

   Recommended Follow-On Research: Model and test new terminal-area well-clear thresholds (Rec. 4.7, 4.10) that account for corridor geometry, vertical/lateral constraints, and proximity to obstacles. Include simulation of both cooperative and non-cooperative traffic.

   Goal: Enable safe, efficient separation by adopting well-clear minima that avoid nuisance alerts but still prevent loss-of-separation in the tight confines of terminal UAM flows.

   b. *Filtering Clutter & Non-Relevant Targets in DAA Sensor Feeds.* Urban radar/ADS-B environments produce high clutter (ground transponders, building reflections) and false tracks (sec. 4.1.2, 2.1.2), which destabilize advisories and overload operators.
   Recommended Follow-On Research: Develop and validate clutter-filtering algorithms and sensor-fusion techniques (Rec. 4.10) for the terminal environment, including integration of ground-based radar data for cooperative/non-cooperative target filtering.

   Goal: Reduce false advisories, improve advisory stability, and ensure DAA alerts are genuinely conflict-driven, enhancing pilot/operator trust and compliance.

   c. *Stable, Predictable DAA Resolution Advisories for Low-Altitude / Hover.* DAA advisories issued during hover/approach phases show high instability and high

non-compliance (sec. 4.1.1, Rorie et al.; sec. 5.3). Low-altitude constraints differ from enroute and must be reflected in RA logic.

Recommended Follow-On Research: Design RA generation algorithms tuned to terminal phases (Recs. 4.9, 5.3) that factor vertical limits, obstacle clearance, and procedural constraints; validate using full-motion, human-in-the-loop simulations with representative RPICs and onboard pilots. This research needs to include a focus on functionality and interface design necessary to ensure effective human-automation interaction.

Goal: Produce RA behavior and RPIC responses that are operationally appropriate, stable, and trusted - improving compliance rates and safety margins in approach and departure flows.

    d. *Integration of Pad / Runway / Surface State into DAA & Arrival Logic.* Current airborne-focused DAA ignores pad occupancy or runway clearance status, risking incursions or arrival conflicts (secs. 4.4.2, 4.5, 2.2).

Recommended Follow-On Research: Integrate vertiport pad-clear sensing (e.g., downward-facing cameras) and reservation/TMI data directly into DAA conflict detection and resolution logic (Recs. 4.28, 2.9-2.13), ensuring final approach advisories reflect real-time surface conditions.

Goal: Prevent pad/runway conflicts by ensuring arrival decision-making accounts for live surface state, improving sequencing and landing safety in high-volume vertiports.

9.1.1.2 Return to Mission
    a. Procedure-Aware Avoidance Maneuvers Constrained by Terminal Rules & Obstacles. Generic avoidance trajectories can cross into opposing lanes, conflict with arrival streams, or violate obstacle clearance zones (secs. 4.1, 4.3.1, 4.13, 5.3).

Recommended Follow-On Research: Develop constraint-aware avoidance and return-to-mission planners (Recs. 4.6–4.8, 4.13, 5.2–5.5) that incorporate corridor "rules of the road," published SIDs/STARs, holding patterns, obstacle data, and terrain constraints.

Goal: Ensure avoidance maneuvers resolve conflicts without creating new hazards in the structured, congested, and obstacle-rich environment of terminal UAM operations.

9.1.1.3 DAA for Autonomous Control
    a. *DAA to Support Autonomous Flight When There is an LC2L Event.* When the communications link for command and control is lost, the aircraft must fly autonomously. A combination of procedures and supporting automation to ensure safe DAA and return to mission must be incorporated to control the aircraft. Procedures may involve clearing the airspace and landing pad to the extent possible. The automation

must deal with any potential violations of separation that remain (Recs. 4.15, 4.17 4.18; sec. 8.1.7.3).

Recommended Follow-On Research: Define expected approaches to the design of airspace and route/corridor structure for Initial Operations Phase 2, Midterm and Mature Operations. For this range of approaches, identify the range of relevant scenarios that could necessitate initiation of an RA and define the range of conditions (such as the presence of traffic and obstacles and any restrictions regarding the structure of traffic flows) that could arise and affect return to mission. Develop and evaluate the logic and interface design requirements necessary for the aircraft to autonomously respond in such scenarios.

It is important to note that the current thinking is pushing much more towards integration rather than segregation. The regulatory hurdles to create exclusive use airspace for UAM would be tremendous.

Goal: Ensure safe DAA and return to mission when there is a loss of communication for command and control.

9.1.1.4 Traffic Flow Management.

a. *Preflight and enroute traffic flow management.* To safely provide separation assurance, the need for DAA software to support the RPIC in maintaining well-clear and in tactically resolving conflicts should be the exception. The same applies to the need for intervention by ATC. Effective traffic flow management must be applied both preflight and while aircraft are enroute to manage both nominal and off-nominal scenarios in order to provide an effective layered approach to safety. This requires a range of automation support for monitoring, situation assessment, planning, replanning and actual management of the air traffic at a strategic level. It also requires automation to support distributed coordination and collaboration among the relevant parties (sec. 2.2). This research needs to consider the range of designs for airspace and routes that could be developed for UAM operations, as these design decisions have important implications for the design of TFM strategies and tools.

An important special case is the management of diversions. A variety of scenarios can arise that require one or more aircraft to divert to different vertiports or emergency landing sites. Given the constraints introduced by limits associated with the available airspace, the number of vertiports and landing sites and the energy supplies for the involved aircraft, unlike the planning of alternate airports for legacy aircraft today, planning for diversions needs to be supported by automation for both preflight and while aircraft are enroute. This includes coordination among vertiport flight managers, ATC, RPICs, FOCs, PSUs, local law enforcement (Recs. 2.6-2.8, 3.2, 4.5; secs. 5.2; 5.3.2, 8.1.7.2).

There are number of TFM strategies that have been applied to legacy operations which have been developed by the FAA-Industry Collaborative Decision Making Program (such as the use of GDPs, AFPs and FCAs), as well as other implementations to support

Trajectory Based Operations (such as TBFM). Analogous strategies can be applied to manage UAM operations. However, there are important differences between legacy TFM operations and UAM operations such that these strategies and the supporting automation cannot be simply transferred without adaptation.

Recommended Follow-On Research: The use cases representing the full range of UAM scenarios requiring TFM need to be identified. This includes consideration of alternative approaches to airspace and route design. Effective TFM strategies and supporting automation then need to be developed and evaluated. This includes new automation and associated controls and displays to support FAA traffic managers, flight dispatchers/flight planners, RPICs, PSU flight managers and vertiport flight managers.

Goal: Develop and evaluate concepts and tools to support traffic flow management in order to help ensure separation assurance.

9.1.2 *Effective Design of Digital Infrastructure for Vertiports*. The FAA needs to develop recommendations for the digital infrastructure needed to complement existing regulations regarding the physical infrastructure for vertiports, as vertiport flight managers will play an important role in managing vertiport operations. Automation is required to provide situation awareness, to support planning and decision making, and to enable effective coordination and collaboration with ATC, TFM, RPICs, FOCs and PSUs (Recs. 2.7, 2.12, 2.16, 2.18, 2.19).

Recommended Follow-On Research: Roles and responsibilities for vertiport flight managers need to be defined for the range of relevant use cases. Supporting automation then needs to be specified and evaluated. This includes recording performance data for post-operation analysis (Rec. 2.15).

Goal: Ensure that vertiport flight managers can effectively contribute to the safe and efficient operation of vertiports.

9.1.3 *Weather Decision Making.* Convective weather and winds in the lower altitudes of urban areas have spatial and temporal features that are different from higher altitude weather patterns and flows. To provide adequate weather data to support UAM weather decision making, there is a need to equip operational UAM aircraft as weather sensors and to share these data over a network, both to provide reliable data for providing more accurate weather models as well as to support real-time decision making.

Advances in weather forecasting models for lower altitudes are also needed. The meteorologists interviewed as part of this study (who also had expertise in GNC systems for UAM aircraft) all agreed that inadequate weather decision making is likely to be a major safety concern if not addressed more adequately through relevant research and resultant improvements in automation supported weather decision making. This includes decisions for traffic flow management, flight planning, go/no go decisions both preflight and while enroute, and diversion decisions while enroute.

Recommended Follow-On Research: Research is needed need to determine how to equip aircraft as weather sensors, to share these data over a network, to use such data to support weather modeling, and to integrate and display such integrated data and information to support the full range of decision making tasks and decision makers.

Goal: Improve weather decision making to increase safety.

9.1.4 *Communication.* To support moderate to high volume UAM operations, digital communication is necessary. Further research is necessary to guide the design of a communication network that supports primary and backup communication systems that can be seamlessly accessed by the UAM aircraft automation, as well as by ATC, RPICs, onboard pilots and staff at PSUs and vertiports. And appropriate interface designs to support communications need to be developed and evaluated.

Recommended Follow-On Research: Research is needed to determine how to equip aircraft as weather sensors, to share these data over a network, to use such data to support weather modeling, and to integrate and display such integrated data and information to support the full range of decision making tasks and decision makers.

Goal: Improve weather decision making to increase safety.

9.1.5 *Risk Assessment.* Numerous methods have been developed to support risk assessment for complex systems. This includes a range of qualitative and quantitative methods. None of these approaches alone provides a silver bullet for the evaluation of safety automation embedded in operational systems for UAM. A combination of approaches can, however, provide converging evidence to increase confidence in the conclusions of a risk assessment.

Recommended Follow-On Research: Studies need to be completed that provide guidance and demonstrate how specific qualitative and quantitative risk assessment methods can be integrated to more fully evaluate the incorporation of safety automation into UAM operations. These studies need to be conducted in the context of realistic UAM operations.

Goal: Improve risk assessment through the integration of established risk assessment methods.

In short, to provide the level of safety necessary for UAM operation, important research needs to be completed in the areas identified above that focus on:
- Separation assurance.
  - DAA.
  - Return to mission.
  - DAA for autonomous control by aircraft.
  - Traffic flow management.
- Effective design of digital infrastructure for vertiports.
- Weather decision making.
- Communication.
- Risk Assessment.

In addition, Appendix B of this report provides a detailed assessment of the gaps in standards to support the technology path for UAM. Standards gaps are categorized and prioritized in this appendix.

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Appendix A: Recommendations for Technology Development and Evaluation

Appendix A identifies recommendations concerning the development and use of technologies to provide safe automation that need to be addressed in the transitions from Initial to Midterm to Mature Operations. Many of these serve to reinforce the importance of current efforts to support the implementation of UAM. Others identify needs that are not, however, currently being addressed. Note that the recommendations below in blue indicate areas with implications for safety automation that require attention from the FAA and/or standards organizations in terms of research and in terms of standards.

- Recommendation 2.1: The sensors and automation necessary to provide good, actionable convective weather and wind information for operators to make preflight decisions about proceeding with a mission, planning a route, or diverting a flight while enroute need to be further developed and tested.

  This includes the need to support networked access to data provided by drones as weather and wind sensors, and the need to develop automation to integrate and display these weather data effectively to support weather decision-making by the full range of users. The information display requirements will vary depending upon the specific user (such as an air traffic controller vs. a remote pilot).

  This also includes the need to develop weather models for urban airspace that provide forecasts based on all of the available weather data.

- Recommendation 2.2: Standards need to be provided for weather sensors and their housing on UAM aircraft, as well as weather modeling techniques.

- Recommendation 2.3: In addition to providing the technologies necessary to support improved weather decision making, UAM safety can also be enhanced by improvements in GNC robustness to better respond to "very windy conditions".

- Recommendation 2.4: As the degree of tactical control by aircraft automation increases to better support remote pilots, onboard automation to assess and generate responses to real-time weather and winds becomes increasingly important and needs to be further developed and tested.

- Recommendation 2.5: The FAA needs to designate the VFR airspace for flight between vertiports. VFR routes may also need to be designed. (The introduction of VFR routes or corridors required significant evaluation, however.) Strategies to deal with higher traffic volumes (such as traffic flow management) need to be considered to manage traffic both for the case where such structured airspace is designated and airspace design where it is not.

- Recommendation 2.6: For each urban area, the FAA needs to define the procedures for entering and exiting ATC controlled holding patterns and go-arounds for flights flying in UAM VFR airspace to fly to vertiports. (For diversions that require exiting UAM VFR airspace, procedures similarly need to be defined.)

- Recommendation 2.7: UAM aircraft need to be consistent with the FAA requirements for power-lifted aircraft (FAA Power-Lifted SFAR, 2024).

- Recommendation 2.8: Aircraft certification by the FAA needs to require that onboard avionics safely support PIC/RPIC performance in off-nominal scenarios requiring responses such as entry and exit from a holding pattern, initiation and completion of a go-around, or a diversion. As an example, the FAA needs to determine whether a "go-around"

button should be required for a UAS as a safety measure to initiate a missed approach when aborting a landing in favor of a new attempt.

- Recommendation 2.9: The FAA needs to require training for pilots and controllers regarding holding patterns and go-around procedures associated with flights arriving at vertiports at airports in Class B, C, and D airspace.
- Recommendation 2.10: The ATCT Traffic Manager at the arrival airport needs to determine the conditions when UAM traffic volume and complexity increase enough to require arrival metering and TFM initiatives. Assuming these conditions exist:
    - o Recommendation 2.11: The FAA needs to specify the assignment of roles and responsibilities for metering and creating TMIs. At airports in Class B, C, and D airspace, specification of arrival rates for metering and the creation of TMIs will be the responsibility of the ATCT Traffic Manager. The roles of ATCT Traffic Managers, FOCs, PICs/RPICs, PSUs, and vertiport flight managers need to be specified. Supporting procedures and technology required of each group need to be developed.

        For airports and landing sites in Class E and G airspace, the FAA needs to specify criteria and an approval process to evaluate proposed staffing, procedures, and supporting automation.
    - o Recommendation 2.12: If sufficient volume and complexity exist, the use of TFM initiatives will be required.
    - o Recommendation 2.13: Automation will be required to manage metering and to create and disseminate Traffic Management Initiatives. This includes automation for the responsible ATCT Traffic Manager to meet the following decision support and TFM requirements:
        - A traffic management display that provides an integrated display of air traffic, weather, terrain, and special use airspace to provide situation awareness and to support decisions relevant to metering of arrivals and the creation of TMIs. For UAM operations, this display needs to provide such information as is relevant to the low-altitude operation of UAM aircraft. The display of information relevant to the bigger picture, including legacy operations, is also necessary in order to provide situation awareness.
        - Flow Evaluation Areas customized for application to display forecasts of traffic loads over time to make decisions about the management of low altitude operations for UAM aircraft.
        - A decision support tool for the ATCT Traffic Manager that -
            - Allows the ATCT Traffic Manager to set arrival rates for each of the different flows (if there is more than one) feeding the vertiports at the airport and communicating that information to the relevant parties. This could require information from the vertiport flight manager regarding the capacity of a vertiport to accommodate arrival rates based on approach procedures and the number of available landing pads. Arrival rates need to be available for longer-term scheduling purposes as well as real-time updates to manage dynamic conditions on the day of operation.

- Allows the ATCT Traffic Manager to create and disseminate TMIs, with input from FOCs and vertiport flight managers. PSUs with appropriate automation might support this dissemination.
- Allows a reservation system manager to translate these arrival rates into assigned release times (OFF times) while also accommodating pop-ups. This will require input from the flight operators regarding airtimes using automation. The assignment of responsibility for reservations to a PSU or the ATCT needs to be determined.
- Allows a TBFM (Time-Based Flow Management) decision support tool to support reassignment and communication of release times shortly before OFF by the ATCT traffic manager based on actual traffic flows. This requires coordination of both the arrival and departure ATCTs for such rescheduling.
  - Recommendation 2.114: For departures controlled by ATC, the release times assigned to individual UAM flights need to be displayed to the ATCT AAM (Advanced Air Mobility) controller.
  - Recommendation 2.15: FOCs and PICs/RPICs need a tool that supports the filing and cancellation of flight plans as well as substitutions, etc. This tool also needs to provide updated information on release times.
  - Recommendation 2.16: The FAA needs to develop recommendations for the digital infrastructure to complement existing regulations regarding the physical infrastructure for vertiports. This includes recording performance data for post-operation analysis.
  - Recommendation 2.17: The FAA needs to develop recommendations for software to support a vertiport flight manager. Specifically, these specifications need to require a ground workstation to maintain situation awareness (weather and traffic), to provide input regarding arrival capacity to the ATCT Traffic Manager when appropriate, and to communicate with ATC, the vertiport ground crew, the PSU if one is established, PICs/RPICs, and FOCs.
  - Recommendation 2.18: All of the stakeholders with operational responsibilities need a tool that displays NOTAMS.
  - Recommendation 2.19: In addition to the above recommendations associated with the management of arrivals and departures associated with vertiports at airports in Class B, C, and D airspace, the FAA needs to establish requirements for the operation of private vertiports in Class G and Class E airspace regarding metering and TMIs. (For such vertiports at airports with low-volume operations, the flights may self-separate and sequence using current procedures for helicopters.)
- Recommendation 2.20. For private vertiports at such airports with higher volume, the FAA needs to establish requirements regarding responsibilities and regarding the process and supporting software for managing the sequencing and spacing of arrivals (as contrasted with public vertiports in Class B, C, and D airspace where ATC will be required to flight follow and will have positive control in case of an off-nominal event).
- Recommendation 3.1: According to the FAA 2028 Implementation Plan, charted VFR routes, holding patterns, and go-around procedures need to be defined. Simulations studying UAM operations at LAX with onboard pilots, however, have indicated that there

will be a need for defined routes and procedures, albeit not necessarily published/charted but rather covered in an LOA or something similar.

- Recommendation 3.2: Procedures need to be developed for the PIC, vertiport staff, and ATC for management of UAM flights that have to deviate from their planned trajectories for diversions, traffic avoidance, and weather. As noted in Section 2.0, such procedures include the responsibility for ATC to control flights that need to be put into holding or need to initiate a go-around.
- Recommendation 3.3: Figure 3 provides a more extensive airspace design that includes a broad area for unstructured VFR airspace around charted VFR routes to reduce the burden on ATC when deviations from the planned route for a flight are required. If volume and complexity reach sufficiently high levels during Initial Operations Phase 1 (with onboard pilots), it may be necessary for the FAA to develop this type of airspace design to reduce the workload for ATC.

In addition to defining procedures (such as required separation distances), additional needs to support the safe operation of remotely piloted aircraft are listed below. Provide:

- Recommendation 4.1: Software to provide the RPIC with situation awareness regarding other traffic and obstacles in the area (enhanced Visual Flight Rule operations).
- Recommendation 4.2: DAA software to support detecting and responding to cooperative and non-cooperative aircraft and obstacles.
- Recommendation 4.3: Software to support return to mission after a maneuver is completed to avoid a conflict.
- Recommendation 4.4: Procedures and equipage with the technology necessary to ensure safe autoflight to an autonomous landing if there is a loss of communication for command and control by the remote pilot.
- Recommendation 4.5: If traffic demand is high enough, an airspace design with unstructured UAM VFR airspace around the charted routes or tracks needs to be considered (see Figure 3) to more effectively allow for deviations around obstacles and diversions.
- Recommendation 4.6: eVTOLs controlled by remote pilots must have ADS-B In/Out to support separation assurance.
- Recommendation 4.7: eVTOLs controlled by remote pilots must have the capability to maintain well-clear for VFR flight in nominal and off-nominal scenarios.
    - Separation from cooperative and non-cooperative aircraft during departure and arrival.
    - Separation from cooperative and non-cooperative aircraft while enroute and during sequencing and spacing for arrival, including separation and sequencing for landing when a flight is in a holding pattern or has a go-around.
    - Separation when one UAM aircraft overtakes another.
    - Separation when two UAM aircraft have crossing trajectories (see Figure 4). For some airspace designs, this scenario may be precluded by the design of the charted routes.

A big challenge here will be how the aircraft responds to alerts when in controlled airspace with a high volume of traffic. For example, suppose a UAM aircraft with an onboard pilot is issued a visual separation clearance with another UAM that has a RPIC.

The piloted aircraft may legally and safely maneuver within the RPIC UAMs DAA's well clear volume which could trigger a resolution even though separation exists.

- Recommendation 4.8: Software to support return to mission after an avoidance maneuver.
- Recommendation 4.9: The FAA needs to develop a requirement for the performance of software supporting DAA and return to mission by remote pilots based on testing of the DAA software using human-in-the-loop evaluations.
- Recommendation 4.10: The FAA needs to determine what is required for separation assurance to ensure safe operations in terms of the design and use of DAA software and airspace design, as well as the contributions of Traffic Manager, ATC, and RPIC performance.
- Recommendation 4.11: The FAA needs to ensure that procedures for managing airborne flights when the ground radar fails have been defined. This could involve diverting to another vertiport (or ditch site) for which ground radar coverage is available.
- Recommendation 4.12: To the extent possible, the FAA should ensure overlapping coverage for the ground radars used by different vertiports.
- Recommendation 4.13: The FAA needs to establish performance recommendations for communications.
- Recommendation 4.14: The FAA needs to establish the communications requirements to support remote pilots and autonomous control of UAM aircraft. These recommendations need to:
  - Identify the full range of communications (content and originators/recipients) that need to be supported.
  - Identify performance recommendations for architectures to provide seamless transition to backup systems for communications if the primary support for communications is lost.
  - Define the procedures and required supporting technologies if there is a loss of communications, supporting specific forms of communication. Standards and supporting communication technology to limit and manage communication delays (command and control and ATC-pilot communications) that are inherent to remote operations. (Existing standards like DO-377B are inadequate.)
- Recommendation 4.15: Assuming the FAA requires the automation necessary to support autonomous control if one or more remotely piloted aircraft lose communication for C2 by the remote pilot, and assuming the FAA requires an aircraft with a remote pilot that loses communication for C2 to autonomously fly its current planned trajectory to its destination, there are several implications:
  - Before departure, the automation must know the full 4D trajectory, including the planned approach path and landing pad. The automation must be updated with any amendment made to this 4D trajectory while the flight is enroute (which is also known by the RPIC). This applies even if the flight is flying along a UAM VFR corridor, as it needs to be prepared to transition to autonomous flight if necessary.
  - The onboard software must be able to determine when communication has been lost for some period of time and then switch to autonomous flight.
  - The software must have autonomy capable of:
    - Autonomous auto-flight prior to reaching the destination vertiport or pre-planned alternate.

- o Autonomous DAA to ensure the aircraft is "well clear" of other aircraft and objects and responds appropriately for collision avoidance.
- o Autonomous "return to mission" if a DAA resolution moves the flight off its planned trajectory (see Figures 5 and 6).
  - ▪ The software not only needs to compute the trajectory to implement a collision avoidance maneuver, but it also needs to compute the trajectory to "return to mission" after this maneuver is completed.
  - ▪ It should be noted that both this autonomous DAA maneuver and the return to mission should take into account airspace procedures and constraints, including the approach path to land at the destination vertiport. An example would be UAM flights flying to a vertiport located in the middle of LAX that need to fly a trajectory that does not conflict with the departure SIDs and arrival STARs used by the aircraft operating on the runways at LAX.
  - ▪ The software also needs to determine whether the flight has a sufficient power supply to fly the computed 4D trajectory and have a contingency plan to deal with a scenario where the power supply is not adequate to land and the planned destination vertiport. If, to reduce the required reserve energy supply to 20 minutes, the flight planner has included a ditch site along the route of flight, the contingency plan could involve diverting to that ditch site.
  - ▪ Autonomous precision auto-land. Note that it also could be desirable for the aircraft to loiter for some short time period at some predefined point on its 4D trajectory to enable clearing of the airspace of other flights as necessary and to ensure that the vertiport landing pad is clear.
  - ▪ Certain other procedures also need to be defined when communication is lost. This includes a requirement that the remote pilot inform the vertiport, and, as appropriate, inform ATC that the aircraft has lost communication. Having received such a notification, an emergency would need to be declared and communicated to all relevant parties (ATC, vertiport staff, and all UAM aircraft with onboard or remote pilots in the area).
- Recommendation 4.16: When a UAM aircraft is filed to fly a VFR route, the flight plan should be disseminated and updated as if it were flying IFR so that the planned route (updated with any amendments while enroute) is known to all parties if there is an LC2L event.
- Recommendation 4.17: Before departure, the automation must know the full 4D trajectory, including the planned approach path and landing pad. The automation must be updated with any amendment made to this 4D trajectory while the flight is enroute (which is also known by the RPIC).
- Recommendation 4.18: The onboard software must be able to determine when communication has been lost for some period of time and then switch to autonomous flight.
- Recommendation 4.19: Detailed analyses are necessary to determine the reliability of the primary and backup communications systems. The FAA needs to establish performance

requirements relative to capacity, latency, reliability, and security. Examples of scenarios where a LC2L event could occur that merit consideration are:

- o Hardware or software failures.
- o Direct attacks on the communications infrastructure itself.
- o Emergency evacuation of a flight operations center, leaving all of its flights unattended.
- o Spoofing of GPS impacting C2 systems that rely on GPS for encryption.

- Recommendation 4.20: Develop requirements for the equipage necessary for conversion of the ATM conversations to digital-only communications with ATC, while maintaining voice communications as a backup
- Recommendation 4.21: Integration of Artificial Intelligence: There are proposals to apply Artificial Intelligence (AI) to standalone 5G technology for UAM control systems and aerial communications networks (Jeong 2023). This introduces unique challenges in terms of the evaluation of such systems for reliability. FAA guidance on this needs to be provided.
- Recommendation 4.22: FAA recommendations are needed specifying performance recommendations for the automation necessary for the vertiport flight manager to:
  - o Support the use of reservations and ground delay programs with a strategy to accommodate different business models (regularly scheduled flights vs. pop-ups), including support for swapping arrival slots within and across flight operators. It is not clear who will be responsible for the reservation system (the FAA vs. each vertiport vs. a PSU).
  - o Provide input regarding vertiport capacity to the ATCT Traffic Manager for setting arrival rates and initiating TFRs, including decisions to initiate departure and arrival ground stops.
- Recommendation 4.23: In terms of recommendations for the design of vertiport airspace, the existing FAA standard (FAA 2022a) for vertiport airspace design (FAA 2022b) applies to vertiports serving UAM aircraft with onboard pilots and UAM aircraft that are remotely piloted. This FAA standard provides specifications for the design of the approach and departure paths for vertiports, defining the "flight track that VTOL aircraft follow when landing at or taking off from a vertiport." (See Figure 9.)
- Recommendation 4.24: The ground control station for the remote pilot and/or flight planner needs to support coordination for pre-departure planning. For the RPIC and flight planner, this includes information displays indicating:
  - o Status of the planned vertiport destination and alternate vertiports (including status of landing pads, parking spots, associated TFRs, and NOTAMS).
  - o Projected traffic demand relevant to departures and arrivals at vertiports.
  - o Scheduled release times for aircraft departures and any revision of these release times closer to wheels up (OFF).
  - o Current and forecast winds, convective weather, and winter weather conditions, as well as other constraints in the vicinity of the departure or arrival vertiport. (Should the vertiport provide real-time, on-site automated weather data, such as Automated Weather Observing Systems (AWOS), to all UAM?)
  - o Flight planning software to support the generation of flight plans (including contingency plans) using the information listed above. Note that this flight planning software needs to determine energy supply Recommendations, including the FAA-required reserves and a sufficient energy supply to divert to planned alternate

landing sites. (This will be addressed in more detail in the section on preflight planning.)

- Recommendation 4.25: The ground control station for the vertiport flight manager needs to support coordination (through software) with the party responsible for setting arrival rates and translating these rates into reservations with associated arrival and departure slots. Either ATC, the PSU, or the vertiport could provide this information to flight planners and RPIC (something that needs to be determined). The flight planners or RPICs would, in turn, be providing these parties with information regarding their proposed flight plans that meet the constraint of the assigned release time for a flight.
- Recommendation 4.26: The report for Task 2 of this project indicates that, if demand is high relative to vertiport capacity, there is a need for pre-flight and real-time coordination if multiple aircraft need to divert from a specific vertiport (due to weather or some other constraint that closes or limits the capacity of one or more vertiports). Software to support this may become necessary if traffic demand is sufficiently high. The process and responsibility for evaluating alternate and approving landing sites, including assignment of the responsibility to complete this process, needs to be determined.
- Recommendation 4.27: For vertiports in ATC-controlled airspace, approvals for proposed departure times will be centralized through an ATCT traffic manager supported by software. Again, the assignment of this responsibility for vertiports that are not in ATC-controlled airspace needs to be determined. Approvals need to be communicated to flight planners and RPICs through software.
- Recommendation 4.28: Requirements for automation to help ensure landing pads are clear for safe landings need to be developed, potentially including the use of downward-facing cameras on the aircraft (McNab 2023).
- Recommendation 4.29: A decision needs to be made regarding the requirements for a vertiport ground station to support the vertiport flight manager.
  - The vertiport flight manager needs access to weather information.
  - The vertiport flight manager needs to have the ability to coordinate with the FAA traffic manager (or some other appropriate authority for vertiports that are not in ATC-controlled airspace) to provide information relevant to determining arrival capacity or to request a vertiport departure or arrival stop. Software supporting the creation of such restrictions needs to be provided. Thus, the following questions regarding the creation and dissemination of traffic flow restrictions need to be addressed:
    - Who has the responsibility and authority to create and disseminate traffic flow restrictions indicating vertiport status? (depending upon whether or not the vertiport is in ATC-controlled airspace)
    - Who should provide input to this decision-making?
    - How will traffic flow restrictions be created and disseminated?
    - What expertise in meteorology and traffic flow management is required for decisions regarding vertiport status?
    - Who has the responsibility and authority to clear a flight for departure? (depending upon whether or not the vertiport is in ATC-controlled airspace)
      - ATC if in ATC-controlled airspace vs. vertiport flight manager? What displays and automation are necessary to support this?

- o Who has the responsibility and authority to manage sequencing and spacing and clear a flight for landing (depending upon whether or not the vertiport is in ATC-controlled airspace)? What displays and automation are necessary to support this?
  - ATC if in ATC-controlled airspace?
- o Who has the responsibility and authority to manage missed approaches (depending upon whether or not the vertiport is in ATC-controlled airspace)? What displays and automation are necessary to support this?
  - ATC if in ATC-controlled airspace?
  - Vertiport flight manager?
  - RPIC or PIC?
- Recommendation 4.30: The interface designs to support remote pilots are expected to differ for each of the eVTOLs under development. As part of the certification process for aircraft flown by remote pilots, performance by RPICs using these interfaces needs to be evaluated for the full range of nominal and off-nominal scenarios.
- Recommendation 5.1 Procedures and software need to be developed to support:
  - o Software for the development and dissemination of TFRs and NOTAMs by the ATCT Traffic Manager. This includes receipt of input from vertiports, ATC, and a meteorologist.
  - o Software to support flight planner preflight development and submission of flight plans for approval. Note that there have been proposals to centralize flight planning by the PSU. A decision regarding this alternative needs to be made.
  - o Software to support PSU traffic manager evaluation of a proposed flight plan for deconfliction (completed automatically by default using PSU flight deconfliction software with management by exception by the PSU traffic).
  - o Software to support coordination among multiple PSUs if there are several.
- Recommendation 5.2: An advanced version of the enhanced Visual Flight Rule software is needed that applies knowledge of the airspace structure, as well as defined vertiport holding patterns and procedures for go-arounds to provide effective situation awareness to the RPIC.
- Recommendation 5.3: The DAA software needs to apply knowledge of the airspace structure, as well as defined vertiport and enroute holding patterns and procedures for go-arounds to provide effective situation awareness and alerts to the RPIC. Consistent with the philosophy of ACAS, the RPIC is alerted and initiates a recommended conflict resolution. A specification of an advanced version of ACAS Xr that considers the structure of the airspace is required to provide this. An open question is whether and when the DAA automation should autonomously initiate a conflict avoidance maneuver.
- Recommendation 5.4: If the RPIC chooses to use the passing lane, an alerting function warns of a potential conflict before a passing maneuver is initiated (see Figures 13 and 14).
- Recommendation 5.5: If communication for C2 is lost as discussed in Section 4.0, the software to initiate and control autonomous flight requires knowledge of the airspace structure (see Figures 12-14) and the planned current 4D trajectories for the other flights in the airspace. When an RPIC amends a route through the autoflight function, this route should be communicated to the PSU, vertiport flight manager, and ATCT controller at the AAM position.
- Recommendation 6.1: Additional research is required to develop and demonstrate an ability to safely and effectively implement the multi-aircraft supervisor concept within the airspace structure assumed for Midterm Operations and continuing to be used in Mature Operations.

(NASA m:N 2024). This will require significant automation support, including a communications infrastructure to support such operations.

- Recommendation 6.2: The concept of dynamic design of new UAM corridors requires the definition of further detail regarding the concept and evaluation of proposed approaches to its implementation (MITRE 2019). This will also require significant automation support.

APPENDIX B. Gaps in Standards

The following tables identify the gaps in standards identified in this research. Current standards that support the technology path were documented in the Task 3 report for this project. In addition to the existing standards, additional standards were identified that need to be completed to support the technology path for UAM. Using the methodology described earlier in this report, standards gaps identified in the Task 3 report for this project were categorized and prioritized. Listed below are standards gaps for each area, which are prioritized to give additional guidance to the FAA to inform further research and standards coordination.

Further discussion of the existing standards for the specific areas identified is provided in Report 3 of this project.

DAA Standards Gap Description:

Gap ID	DAA Gap Description
G01	DAA Display and Control Functions
	Lack of performance standards for DAA displays and control functions used by Remote Pilots in Command (RPIC) and autonomous systems during Initial Operations Phase 2 and beyond.
G02	Ground Control Station Information Requirements
	No standards exist for what information must be available to RPICs in Ground Control Stations, especially for semi-autonomous operations (e.g., separation distances, degraded
G03	Structured Airspace for UAM Corridors
	Absence of standards for DAA technology to operate effectively in structured airspace like one-way tracks and dynamic corridors proposed for Midterm and Mature UAM Operations.
G04	Autonomous Maneuver Execution
	No standards guiding autonomous DAA systems to command and autopilot to execute immediate maneuvers in dense urban airspace without pilot intervention.
G05	Integration with ACAS Xr and Airspace Design
	Few standards exist to incorporate new airspace designs and procedures (e.g., ACAS Xr, NASA concepts) into DAA systems.
G06	AI-Enabled DAA Algorithms
	Lack of standards for validation and deployment of AI-enabled DAA systems that anticipate conflicts using traffic and weather data.
G07	Multi-Aircraft Supervisors
	No standards for managing multiple aircraft by a single RPIC, including interface and control requirements.
G08	Autonomous Conflict Resolution and Return to Mission
	tandards are missing for autonomous conflict resolution and mission continuation in case of loss of command and control (LC2L).
G09	Minimum DAA Equipment by Operation Type
	No defined standards specifying minimum DAA equipment requirements based on the type of UAM operation.
G10	Airspace Capacity Requirements
	Standards are needed to define airspace capacity thresholds and how DAA systems should respond to congestion.
G11	Communication Standards (e.g., VoIP)
	Gaps exist in standards for communication technologies like voice over internet protocols used in UAM operations.
G12	Traffic Manager Standards and Training
	No standards for traffic manager roles, responsibilities, and training in UAM environments.
G13	Ground Control Station Interface Design Communication Standards (e.g., VoIP)
	Missing standards for interface design and functionality of ground control stations used in DAA operations.
G14	Visual Systems for UAM Landing
	No standards for visual systems required for safe UAM landing operations.

DAA Standards Prioritization Scoring:

Gap ID	Safety Impact (S1) [0-10]	Operational Dependency (S2) [0-10]	Time Criticality (S3) [0-10]	Implementation Complexity (S4) [0-10]	Weighted Score	Priority Level	Rank
G01	10	9	9	8	9.2	HIGH	1
G02	8	6	8	6	7.1	HIGH	6
G03	6	6	6	6	6	MEDIUM	10
G04	4	4	5	4	4.2	MEDIUM	13
G05	10	9	9	8	9.2	HIGH	1
G06	5	6	4	5	5.1	MEDIUM	11
G07	4	4	4	6	4.3	MEDIUM	12
G08	9	7	8	8	8.05	HIGH	4
G09	3	3	4	6	3.65	LOW	14
G10	4	3	3	3	3.35	LOW	15
G11	10	8	6	7	8.15	HIGH	3
G12	7	6	8	4	6.45	MEDIUM	7
G13	7	6	6	6	6.35	MEDIUM	8
G14	9	6	8	8	7.75	HIGH	5
G15	7	6	7	4	6.25	MEDIUM	9

Vertiport Standards Gap Description:

Gap ID	DAA Gap Description
G01	Structured Airspace Design for Vertiports
	No standards exist for designing approach and departure airspace for high-volume vertiport operations, especially under mixed pilot/RPIC environments.
G02	Vertiport Flight Manager Automationound Control Station Information Requirements
	Lack of standards for automation systems to support vertiport flight managers in sequencing, clearance, and traffic coordination.
G03	Remote Pilot Ground Control Station (GCS)
	No defined standards for RPIC GCS interfaces, critical information displays, and integration with vertiport
G04	Reservation and Prioritization Systems
	Absence of standards for vertiport reservation systems and prioritization protocols for critical flights (e.g., medical transport).
G05	Low-Altitude Separation and Right-of-Way Rules
	No established standards for separation and right-of-way in low-altitude vertiport airspace, especially for DAA-equipped aircraft.
G06	Automation for Traffic Demand and Weather Forecasting
	Standards are needed for automation systems that display projected traffic demand and weather conditions relevant to vertiport operations.
G07	Integration with Local Ecosystem and Airports
	No standards guiding vertiport integration with nearby airports, general aviation, and local traffic using automated communication systems.
G08	Digital Architecture and Cybersecurity
	Lack of standards for secure digital infrastructure, including cybersecurity protocols for vertiport automation and remote operations.
G09	Automated Charging and Refueling Systems
	No standards for automated ground systems to support charging/refueling of eVTOLs at vertiports.
G10	Performance Data Collection and Analysis
	Absence of standards for routine collection, archiving, and analysis of vertiport operational performance
G11	Contingency Landing and Missed Approach Automation
	No standards for automated decision-making in missed approaches or emergency landings due to limited hover time and energy reserves.
G12	Visual Guidance and Fiducial Markers
	Standards are needed for visual aids like QR-style fiducial markers to guide precise landings and pad
G13	Micro-weather Monitoring and Bird Detection
	No standards for real-time micro-weather systems and bird detection with dynamic flight replanning
G14	Automation for TLOF/FATO Area Safety
	Standards are missing for automated systems to ensure clear and safe TLOF/FATO areas during arrivals and departures.
G15	Training Framework for Remote Pilots
	No formal standards for remote pilot licensing, aircraft-per-pilot ratios, and maintenance certification.

Vertiport Standards Prioritization Scoring:

Gap ID	Safety Impact (S1) [0-10]	Operational Dependency (S2) [0-10]	Time Criticality (S3) [0-10]	Implementation Complexity (S4) [0-10]	Weighted Score	Priority Level	Rank
G01	10	9	9	8	9.2	HIGH	1
G02	8	6	8	6	7.1	HIGH	6
G03	6	6	6	6	6	MEDIUM	10
G04	4	4	5	4	4.2	MEDIUM	13
G05	10	9	9	8	9.2	HIGH	1
G06	5	6	4	5	5.1	MEDIUM	11
G07	4	4	4	6	4.3	MEDIUM	12
G08	9	7	8	8	8.05	HIGH	4
G09	3	3	4	6	3.65	LOW	14
G10	4	3	3	3	3.35	LOW	15
G11	10	8	6	7	8.15	HIGH	3
G12	7	6	8	4	6.45	MEDIUM	7
G13	7	6	6	6	6.35	MEDIUM	8
G14	9	6	8	8	7.75	HIGH	5
G15	7	6	7	4	6.25	MEDIUM	9

Communications Standards Gap Description:

G01	Lack of an integrated, aviation-grade C2 link standard that couples command, control, and guidance for dense
	There's no unified, aviation-grade standard that ties C2 links to clear guidance/control for dense urban AAM operations.
G02	Fragmented SDO landscape (3GPP/RTCA/EUROCAE) prevents unified C2 requirements and conformance profiles.
	Standards bodies aren't aligned, so everyone builds to different rules.
G03	No standardized handoff processes or real-time visibility for transitions between uncontrolled urban airspace
	Missing common processes and real-time situational visibility for transitioning between uncontrolled urban volumes and ATC-controlled airspace.
G04	ATC infrastructure is not designed for low-altitude, high-volume AAM traffic, increasing workload and reducing
	Existing ATC concepts, tools, and staffing aren't built to manage high-density, low-altitude AAM flows, reducing predictability and increasing workload.
G05	Absence of industry cybersecurity baselines for C2 (encryption, authentication, anti-spoofing/jamming/DoS).
	The control link isn't protected by agreed security rules, so it can be hacked or jammed.
G06	Reliance on unlicensed spectrum without interference-management standards undermines link performance.
	Using busy unlicensed bands without rules for interference hurts connection quality.
G07	Missing performance-based, interoperable communication standards tailored to dynamic AAM environments
	No cross-vendor, performance-based communication standards tailored to dynamic AAM conditions and mixed urban environments.
G08	Undefined integration of Detect-and-Avoid (DAA) with navigation and flight-control systems in shared urban
	Lack of specified interfaces/behaviors for closing the loop from Detect-and-Avoid alerts to navigation/flight-control actions in shared urban airspace.
G09	Lack of harmonization between aviation communications and 5G/6G networks to safely exploit high-
	Aviation communications aren't aligned with 5G/6G features (QoS, slicing, handoff, MEC), limiting safe use of high-bandwidth/low-latency networks.
G10	No standard BVLOS voice/data protocols among remote pilots, ATC/ground control, and onboard passengers.
	There's no standard way for remote pilots, ATC, and people onboard to talk and share data beyond line-of-sight.
G11	Need for secure, low-latency end-to-end architectures that mesh legacy aviation links with emerging networks.
	Underspecified architectures for end-to-end, low-latency, secure communications that combine legacy aviation links with new networks.
G12	No cybersecurity framework for remote-piloting environments (access control, monitoring, incident response).
	Missing policies/controls for access, monitoring, incident response, and resilience specific to remote pilot stations and ops centers.
G13	Absent standards for human-automation teaming around DAA-assisted decision-making in complex/edge
	Lack of guidance on roles, HMI, and procedures for DAA-assisted decision-making in complex/edge cases.
G14	Missing automation-to-automation data-exchange/UTM performance specs for vehicles, UTM systems, and
	No agreed performance specs/protocols for machine-to-machine data exchange among vehicles, UTM providers, and vertiports (rates, latency, reliability).
G15	No QoS/congestion-control and latency/reliability guarantees for high-density communications nodes and
	Absent end-to-end quality-of-service and congestion-management standards for high-density nodes/links to ensure predictable latency/reliability.
G16	Lack of real-time clearance-coordination technology and shared situational awareness across operators and
	Lack of standardized tech/processes for real-time clearance coordination and shared situational awareness across operators and ATC.
G17	Undefined reliability/continuity requirements for C2 links to assure flight continuance in urban operations.
	Missing explicit reliability/continuity (e.g., availability, drop-out tolerance, recovery times) targets for C2 links in urban AAM.

Communications Standards Prioritization Scoring:

Gap ID	Communication Gap Description	Safety Impact (S1) [0-10]	Operational Dependency (S2) [0-10]	Time Criticality (S3) [0-10]	Implementation Complexity (S4) [0-10]	Weighted Score	Priority Level	Rank
G01	Lack of an integrated, aviation-grade C2 link standard	10	8	10	8	9.1	HIGH	1
G02	Fragmented SDO landscape (3GPP/RTCA/EUROCAE) p	6	6	6	8	6.3	MEDIUM	11
G03	No standardized handoff processes or real-time visibi	8	6	8	6	7.1	HIGH	5
G04	ATC infrastructure is not designed for low-altitude, hig	8	6	6	8	7	HIGH	8
G05	Absence of industry cybersecurity baselines for C2 (er	10	8	10	8	9.1	HIGH	1
G06	Reliance on unlicensed spectrum without interference	8	6	8	6	7.1	HIGH	5
G07	Missing performance-based, interoperable communic	8	6	6	8	7	HIGH	8
G08	Undefined integration of Detect-and-Avoid (DAA) with	8	6	8	6	7.1	HIGH	5
G09	Lack of harmonization between aviation communicati	8	8	8	8	8	HIGH	4
G10	No standard BVLOS voice/data protocols among remo	6	6	6	4	5.7	MEDIUM	12
G11	Need for secure, low-latency end-to-end architecture	4	4	2	6	3.9	LOW	13
G12	No cybersecurity framework for remote-piloting envir	6	6	8	6	6.4	MEDIUM	10
G13	Absent standards for human-automation teaming aro	4	2	4	4	3.4	LOW	15
G14	Missing automation-to-automation data-exchange/UT	4	4	2	4	3.6	LOW	14
G15	No QoS/congestion-control and latency/reliability gua	8	8	10	8	8.4	HIGH	3
G16	Lack of real-time clearance-coordination technology a	6	4	6	4	5.1	MEDIUM	14
G17	Undefined reliability/continuity requirements for C2 l	8	6	6	6	6.7	MEDIUM	10

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Preflight, strategic deconfliction, and Preflight Checks Standards Gap Description:

Gap ID	Preflight, strategic deconfliction, and preflight checks Gap Description
G01	Autonomous Flight System Integrity Standard
	Needed to ensure safe, predictable behavior of autonomous UAS; IEEE P7009 is still in draft.
G02	UAS Navigation System Performance and Reliability Standard
	Critical for accurate positioning and safe routing, especially in dense urban environments.
G03	UAS Detect and Avoid Interoperability Standard
	Essential for preventing mid-air collisions and enabling automated separation.
G04	UAS Human Safety Risk Mitigation Standard
	Required to assess and reduce injury risks during flight over populated areas.
G05	UAS Weather Resilience and Data Integration Standard
	Ensures safe operation under varied weather conditions and reliable weather
G06	UAS Maintenance and Inspection Protocol Standard
	Supports long-term reliability and airworthiness of UAS fleets.
G07	UAS Emergency and Hazard Response System Standard
	Needed for onboard and ground-based systems to manage unexpected threats.
G08	Advanced Vertiport Infrastructure and Safety Standard
	Builds on ASTM F3423 but requires expansion for high-density UAM hubs.
G09	Strategic Deconfliction and ATC Coordination Standard
	Enables safe coexistence of UAM with traditional aviation in controlled airspace.
G10	UAS Software Assurance and Autonomy Lifecycle Standard
	Supports scalable automation and software validation across platforms.
G11	UAS Data Exchange and System Interoperability Standard
	Ensures seamless communication between UAS, PSU, ATC, and other
G12	UAS Ground Facility Design and Operational Standard
	Addresses layout, safety, and operational protocols for UAS service facilities.

Preflight, strategic deconfliction, and Preflight Checks Standards Prioritization Scoring:

Gap ID	Preflight, strategic deconfliction, and preflight checks Gap Description	Safety Impact (S1) [0-10]	Operational Dependency (S2) [0-10]	Time Criticality (S3) [0-10]	Implementation Complexity (S4) [0-10]	Weighted Score	Priority Level	Rank
G02	UAS Maintenance and Inspection Protocol Standard	10	10	8	10	9.6	HIGH	1
G10	Advanced Vertiport Infrastructure and Safety Standard	10	10	10	6	9.4	HIGH	2
G06	Strategic Deconfliction and ATC Coordination Standard	10	8	8	10	9	HIGH	3
G01	Autonomous Flight System Integrity Standard	10	6	8	8	8.1	HIGH	4
G11	UAS Detect and Avoid Interoperability Standard	10	6	8	8	8.1	HIGH	4
G12	UAS Emergency and Hazard Response System Standard	10	6	6	10	8	HIGH	5
G07	UAS Human Safety Risk Mitigation Standard	10	6	6	4	7.1	HIGH	6
G03	UAS Weather Resilience and Data Integration Standard	8	6	6	8	7	HIGH	7
G08	UAS Software Assurance and Autonomy Lifecycle Standard	8	6	6	8	7	HIGH	7
G04	UAS Data Exchange and System Interoperability Standard	8	6	6	8	7	HIGH	7
G09	UAS Navigation System Performance and Reliability Standar	6	6	6	4	5.7	MEDIUM	8
G05	UAS Ground Facility Design and Operational Standard	8	4	4	4	5.4	MEDIUM	9

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