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16. Abstract Urban air mobility (UAM) holds the potential to revolutionize public transportation by enabling transportation connectivity between urban centers, suburban hubs, regional airports, and major airports within a region. The new airspace users shall operate alongside traditional manned traffic, UAS operating under UTM, and other UAM traffic. Work package 3 of the ASSURE A36 project seeks to identify the impact of UAM on the National Airspace System with respect to air traffic control, infrastructure, and operations. It seeks to provide recommendations toward future technological developments, approaches to UAM airspace integration, infrastructure enhancements, and new regulations, policies, and procedures to support UAM flights in the NAS. This report represents the team's first project milestone a literature and data review to identify past work addressing UAM-relevant airspace and operational constraints, infrastructure requirements, communication, navigation, and surveillance (CNS) requirements, and the current industry tends toward UAM maturity.		

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AAM	Advanced Air Mobility
AC	Advisory Circular
ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependent Surveillance – Broadcast
ADS-R	Automatic Dependent Surveillance – Re-broadcast
AFCM	Automated Flight and Contingency Management
AGL	Above Ground Level
AIXM	Aeronautical Information Exchange Model
ANSP	Air Navigation Service Provider
APRS	Automatic Packet Reporting System
ATM	Air Traffic Management
ATN	Aeronautical Telecommunication Network
ATS	Air Traffic Service
AFR	Autonomous Flight Rules
AVFR	Augmented Visual Flight Rules
BLOS	Beyond Line of Sight
BVLOS	Beyond Visual Line of Sight
CAAC	Civil Aviation Administration of China
CAAM	Canadian Advanced Air Mobility
CFR	Code of Federal Regulation
CNS	Communication, Navigation, Surveillance
CONOPs	CONcept of OPerationS
CPDLC	Controller Pilot Data Link Communications
CTOL	Conventional Take-Off and Landing
C2	Command and Control
DAA	Detect and Avoid
DDC	Dynamic Delegated Corridors
DFR	Digital Flight Rules
DFW	Dallas Fort Worth International Airport
EASA	European Union Aviation Safety Agency
EO	Electro-Optical Sensor
EPA	Environmental Protection Agency
eVTOL	Electric Vertical Take-Off and Landing
FAA	Federal Aviation Administration
FCC	Federal Communications Committee
FIMS	Flight Information Management System
FIXM	Flight Information Exchange Model
FLS	Forward Looking Sensors
FMS	Flight Management System
GA	General Aviation
GBAS	Ground Based Augmentation System
GCS	Ground Control Station
GDP	Gross Domestic Product

GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
IP	Integer Programming
IR	Infrared Sensor
IRS	Inertial Reference System
ISSA	In-time System-wide Safety Assurance
LAAS	Local Area Augmentation System
LEO	Low Earth Orbit
LiDAR	Light Detection and Ranging
LOS	Line of Sight
METAR	Meteorological Aerodrome Reports
MOCA	Minimum Obstacle Clearance Altitude
MSL	Mean Sea Level
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NG-FMS	New Generation Flight Management System
NOTAM	Notice to Airmen
NUAIR	Northeast UAS Airspace Integration Research Alliance
OCC	Operations Control Center
ODM	On-Demand Mobility
PBN	Performance-Based Navigation
PIC	Pilot in Command
PIREP	Pilot Report
PSU	Provider of Services for Urban Air Mobility
RCE	Remote Component Environment
RMSS	Resource Management and Scheduling Service
RNAV	Area Navigation
RNP	Required Navigation Performance
RPIC	Remote Pilot in Command
RTK	Real-Time Kinematics
RUTM	Regional Unmanned Traffic Management
R&D	Research and Development
SAR	Search and Rescue
SDSP	Supplemental Data Service Provider
SSS	Sequencing, Scheduling, and Spacing
STOL	Short Take-Off and Landing
sUAS	Small Unmanned Aircraft System
SWIM	System-Wide Information Management
TCAS	Traffic Collision Avoidance System
UAM	Urban Air Mobility
UAS	Unmanned Aircraft Systems

UKRI	United Kingdom Research and Innovation
UML	Urban Air Mobility Maturity Level
UOE	Urban Air Mobility Operational Environment
UPP	Unmanned Traffic Management Pilot Program
UREP	Unmanned Aircraft Systems Report
USS	Unmanned Traffic Management Service Supplier
UTM	Unmanned Traffic Management
VAS	Vertiport Automation System
VFR	Visual Flight Rules
VLOS	Visual Line of Sight
VMC	Visual Meteorological Conditions
VTOL	Vertical Take-Off and Landing
V2V	Vehicle to Vehicle
WAAS	Wide Area Augmentation System
WXXM	Weather Information Exchange Model

EXECUTIVE SUMMARY

Urban air mobility (UAM) holds the potential to revolutionize public transportation by enabling transportation connectivity between urban centers, suburban hubs, regional airports, and major airports within a region. The new airspace users shall operate alongside traditional manned traffic, UAS operating under UTM, and other UAM traffic. Work package 3 of the ASSURE A36 project seeks to identify the impact of UAM on the National Airspace System (NAS) with respect to Air Traffic Control (ATC), infrastructure, and operations. It seeks to provide recommendations toward future technological developments, approaches to UAM airspace integration, infrastructure enhancements, and new regulations, policies, and procedures to support UAM flights in the NAS.

The research team surveyed literature from academic, government, and industry sources addressing topics relevant to UAM/NAS integration. The research questions seek to understand: the timeframe for which the UAM market is expected to develop, the minimum operational, system, and procedural requirements of UAM, the Communication Navigation and Surveillance (CNS) requirements of UAM vehicles and supporting infrastructure, the impact of UAM on ATC workload, the infrastructure requirements for UAM, plans for non-segregated operations of UAM, UTM, and manned traffic, recent industry advancements, and vertiport design/planning practices.

The team collected over 130 articles and shortlist only 76 publications for the review process using a reference and citation manager to track each document's citation, full-text, and annotations. Articles were organized by research questions, where some articles often addressed more than one of them. The team reviewed mapped articles, removing duplicates and capturing information that addresses each research question either partially or in full. These notes with citations were organized into the report's narrative that attempts to explain the current state-of-the-art technologies and trends toward future development for each question.

The research team found two major Concepts of Operations (CONOPs) guiding much of the recent research surveyed within the report. One prepared on behalf of National Aeronautics and Space Administration (NASA) provides multiple UAM maturity levels with a fairly ambitious timeline for the UAM market to reach each level of maturity. The Federal Aviation Administration (FAA) also produced the UAM CONOPs v1.0, which presents a future state of UAM similar to NASA's UAM Maturity Level (UML-4).

The UAM system, operational, and procedural requirements must leverage the work performed to date to enable UTM integration into the NAS. With the additional air traffic, Providers of Service for UAM (PSUs) must coordinate traffic within the PSU network and plan flight operations with consideration for the airspace congestion of urban environments, the location of nearby airspaces, weather restrictions, ATC coordination, and enabling greater use of automation. The information must be also shared with UAM operators, PSUs, Unmanned Traffic Management Service Suppliers (USSs), the FAA, and other stakeholders.

To achieve safety of operations within urban airspace, the CNS requirements of the UAM vehicle and the systems necessary to achieve those requirements need to be developed and established. Technologies, such as performance-based navigation, shall enable UAM to operate in environments with greater traffic density and help mitigate the impact of UAM on others' access to the airspace.

If ATC were to treat UAM as regular air traffic today, with low numbers of new entrants and low altitudes the overall increase to ATC workload would be minimal. However, the our literature survey showed that as the UAM traffic density scales upward, the roles and responsibilities of ATC personnel in addressing UAM systems must be decreased in scope to avoid workload scaling upward with the number of UAM aircraft. For this reason, like with UTM using UAS Service Suppliers (USS), PSUs are delegated airspace management responsibilities for UAM with necessary coordination between ATC and UAM for situational awareness and handling off-nominal conditions. These roles include flight planning and traffic sequencing within UAM corridors.

Infrastructure improvements shall be required to support UAM physically and operationally. Essential infrastructure needs to include vehicle-to-vehicle communication networking, enhanced situational awareness tools, air-to-air and air-to-ground data exchange protocols, and C2 links. The location and number of vertiports or Take-Off and Landing Areas (TOLAs) impact the overall airspace with greater traffic for the NAS with vertiports near airports and greater demand for vertiports near services or customer attractions. Multi-modal transportation research and simulation tools can help guide the design of UAM corridor networks and the location of vertiports of various types (vertistops, vertihubs, and multiports). Surveillance infrastructure must also be considered to aid in the tracking of UAM aircraft by PSUs.

The research team identified the following research gaps from the literature review. These gaps include open questions posed by the UAM community and gaps identified by the A36 team.

- What are the operational constraints of UAM corridors?
- What are the operational constraints of UAM vertiports?
- What minimal CNS requirements are necessary to achieve non-segregated UAM requirements?
- What are the roles and responsibilities of the PSU vs. ATC with respect to UAM flight planning, surveillance, information exchange, deconfliction, and contingency management?
- What data exchange must be supported by ATC with UAM stakeholders?
- What UAM system characteristics, infrastructure, and operational requirements influence ATC workload?
- What factors influence vertiport infrastructure design and planning?

By addressing these open questions through WP3 or future ASSURE research, the FAA will be better prepared to delegate resources where appropriate to ensure that ATC integration is coordinated, planned, and delivered to meet the market growth of UAM without compromising NAS safety.

1 INTRODUCTION

To enable the integration of Urban Air Mobility (UAM) and, more broadly, Advanced Air Mobility (AAM) within the transportation networks of our urban environments, the UAM ecosystem must achieve compatibility with the National Airspace System (NAS) and other novel air management environments such as Unmanned Aircraft System (UAS) Traffic Management (UTM). Work Package 3 of the ASSURE A36 project (WP3) seeks to identify the impact of UAM on the NAS with respect to Air Traffic Control (ATC), infrastructure, and operations.

This report examines literature from a variety of sources to identify potential UAM use cases; articulate the airspace equipage, procedures, and infrastructure required to enable UAM integration at varying levels of UAM Concept of Operations (CONOPs) maturity; and understand what existing work has been performed by industry, government, and academia to identify and address UAM integration challenges. The team shall also leverage insight from other work such as international Beyond Visual Line of Sight (BVLOS) standards and proposed concepts for other new entrants into the NAS (e.g., commercial space operations).

1.1 Scope

This research task shall investigate the impact of UAM on the NAS as new operations are integrated into both traditional Air Traffic Management (ATM) systems and their procedures, and/or into the UTM framework.

Research questions addressed by this literature review include:

- What timelines for UAM/AAM capabilities are proposed by academia, industry, government, or other relevant stakeholders?
- What are the minimum system, operational, and procedural requirements necessary to enable UAM integration?
- What Communication, Navigation, Surveillance (CNS) requirements/best practices are necessary for UAM integration?
- What is the impact of UAM integration on air traffic controller workload?
- What are the infrastructural requirements necessary to support UAS integration into NAS (including terminal environments)?
- What strategies exist to coordinate non-segregated operations between the UAM and non-UAM air traffic?
- What are recent industry advancements toward UAM integration globally?
- What factors influence vertiport infrastructure design and planning?

1.2 Background

1.2.1 Distinguishing AAM, UAM, UTM, and ODM

With the multitude of related systems and associated acronyms, this section serves to define four fundamental terms:

- ***Unmanned Aircraft System Traffic Management (UTM)*** is a traffic management system complementary to ATM that identifies services, responsibilities, architecture, data exchange practices, performance, etc., for low altitude sUAS operations.
- ***Urban Air Mobility (UAM)*** is a transportation system or a set of systems that will work on incorporating autonomous aircraft serving low-level altitudes within the airspace of urban environments.
- ***Advanced Air Mobility (AAM)*** is an initiative by NASA, FAA, and other aviation industry stakeholders that builds upon UAM concept to develop a transportation system for transporting people and cargo between local, regional, intraregional, and other areas that currently receive little to no aviation services and are not specific to urban environments.
- ***On-Demand Mobility (ODM)*** is very similar to UAM, where automated, electric-powered aircraft provide high-speed on-demand transportation services to the public, which differs from scheduled AAM operations such as public transit/metro services. In the context of this study, ODM and UAM are used interchangeably without any specific distinction in provided services or principles of operations.

1.2.2 UAM Concepts of Operations

There are currently two concepts of operations, one presented by the FAA and one by NASA. Both CONOPs describes an operational environment that will support the growth of UAM operations in and around densely populated urban areas in the United States. Their goal is to develop an air transportation system within major urban centers and between regions that will allow a safe and gradual transition from traditional ATM to a system that incorporates low-altitude operations of manned and autonomous aircraft operations within those environments. This system will be able to sustain hundreds of simultaneous low-altitude UAM operations.

While both CONOPs describe a similar UAM operating environment, their application and organization of airspace structure are different. NASA defines a UAM Operational Environment (UOE) with a free-flight concept. The FAA envisions established corridors with UAM flights adhering to flights solely within those structures for nominal scenarios. Another main difference between the two is in the scale of initial implementation. The FAA's initial goal for UAM incorporation into the NAS is to use the current operational blueprint and infrastructure, such as helicopter routes and helipads as a template for further development of UAM airspace design. However, NASA is aiming to reach pre-defined UML-4 level of maturity within the same time span, which entails hundreds of UAM operations with reduced separation requirements and in low-visibility conditions. Other differences between concepts of operations are in operational assumptions, specifics relative to the regulations and aircraft certification, vertiport vs. aerodrome definitions, etc.

1.3 Literature Review Approach

The WP3 research team followed an iterative process to survey and analyze literature addressing UAM integration into the NAS.

The team identified the research questions discussed in the preceding section. Using the research questions as guides, the team collected literature from academic research, industry publications, and government reports, storing these works using an online reference management system, Mendeley.

With a collection of references with full text documents, the team reviewed the publications cross-referencing each with the research question(s) and their associated sub-topics. The team observed from the mapping to articles to research question/subtopic that some topics overlapped, which enabled the team to identify the sections and sub-sections to be used in the final report, which are discussed in the Document Organization subsection.

Each section of this report presents the surveyed literature through summaries. These summaries are organized to provide a narrative that addresses each research question.

In the conclusion section, the team presents the lessons learned from the literature, including key patterns observed across sources and noteworthy results from surveyed works.

1.4 Organization of Literature Review

Section 2 of this report presents ERAU's literature review addressing the primary research questions as presented in Section 1.

The survey begins in Section 2.2 to examine research studies addressing the minimum system, operational, and procedural requirements to enable UAM integration. In Section 2.3, the requirements for CNS technologies to enable UAM integration and maturity are explored, breaking down the elements of CNS, approaches for UAM separation, and addressing flight planning by PSUs. Section 2.4 examines factors of UAM integration that can potentially impact ATC workload and proposed mitigations to minimize this impact. Section 2.5 considers the infrastructure needs both physically and technologically to understand how infrastructure influences UAM integration challenges and how UAM integration requirements shall impact the needs for additional infrastructure development. Section 2.6 considers approaches for ensuring manned and other non-UAM air traffic are safely separated from UAM traffic. Section 2.7 examines the recent advances by industry toward UAM integration and development. Section 2.8 examines vertiport infrastructure design and planning.

Section 3 concludes the document with a list of lessons learned while addressing the research questions. Research gaps are identified that must be addressed within WP3 or future ASSURE research.

Section 4 provides a comprehensive list of cited works.

2 LITERATURE REVIEW

The research team's survey addresses the research questions presented in Table 1. Starting with Section 2.1 onward, each subsection addresses a research question as ordered in the table as shown.

Table 1. A36 Research Questions.

RQ0	What timelines for UAM/AAM capabilities are proposed by academia, industry, government, or other relevant stakeholders? (Section 2.1)
RQ1	What are the minimum system, operational, and procedural requirements necessary to enable UAM integration? (Section 2.2)
RQ2	What CNS requirements/best practices are necessary for UAM Integration? (Section 2.3)
RQ3	What is the impact of UAM integration on air traffic controller workload? (Section 2.4)

RQ4	What are the infrastructural requirements necessary to support UAS integration into NAS (including terminal environments)? (Section 2.5)
RQ5	What strategies exist to coordinate non-segregated operations between the UAM and non-UAM air traffic? (Section 2.6)
RQ6	What are recent industry advancements toward UAM integration? (Section 2.7)
RQ7	What factors influence vertiport design and planning? (Section 2.8)

2.1 Proposed Timeline of AAM Development and Integration

As UTM and UAM emerge as new airspace concepts whose growth depends upon advances in both technologies and markets, this section surveys the anticipated timelines of their maturity and implementation. The European Union Aviation Safety Agency (EASA) (2021) indicated that all 76 analyzed publications chosen for their UAM study were published no earlier than 2017, showing a significant interest in the topic in recent years. While EASA does not indicate an exact year for entry into the market, their analysis showed that most of their surveyed sources indicated year 2025 most commonly, with autonomous operations starting around 2030. The most common entry services include air-taxi, drone delivery, and Search and Rescue (SAR) operations EASA will publish its Urban Air Mobility (UAM) draft regulations for UAS and eVTOL aircraft certification in 2023 and plans to publish its draft rules on drone commercial services in cities. EASA will be starting work on a pilot project to work on-line platform for local bodies involved in UAM.

Looking at more detailed year-to-year developments, both Dietrich (2020b) and Mendonca (2020) analyzed the growth opportunities for AAM and UAM for the upcoming decades. For the first few years, efforts shall be focused on testing, urban planning, and public acceptance, which also coincides with NASA’s UAM Maturity Level (UML)-1, i.e., UML-1, according to Mendonca (2020). Mendoca (2022)’s briefing, presents an aggressive timeline for UAM. Under their timeline, low volume operations are expected to begin as early as 2023 with some changes to airspace structure and a gradual increase in volume and complexity within the following year; also indicating the first signs of UML-2. The timeline set forth by Mendonca (2022) does not seem likely as it is anticipated that the first type certificates will not be issued until fall 2024. Through 2025 and 2026, AAM is likely to further expand with infrastructural upgrades via vertiport build-out and scale up the volume of UAM operations, solidifying transfer into the UML-3 phase. By 2030, they project the UAM market to establish within the NAS with expanded networks, areas of usage, and increased automation, which denotes the beginning of the UML-4 stage. From 2030 and onward, AAM is expected to increase in frequency and volume of operations to enter the mature stage within the following five years. Lineberger et al. (2021) similarly projected a timeline of events based on the analysis of AAM industry development today. In the first years of development, they expect AAM operators to finish the Research and Development (R&D) phase and start conducting testing and basic piloted operations. In 2025, the initial low-volume deployment was forecasted to begin with individual cities. In turn, the low-altitude deployments are expected to pave the way for infrastructure development and primary operations with limited automation within the next couple of years. The main difference between these projections is a significant slow-down of industry growth after the first two decades of implementation, as highlighted in Lineberger et al. (2021). By 2034, Lineberger et al. (2021)expect the volume of operations to upscale with significant advances in automation in specific urban, suburban, and rural areas, with a full-scale deployment with full automation to occur only by 2042.

For UAM to be successfully established in day-to-day operations, exploration of the industry's expectations is crucial for the market entry of this type of transportation. Kunchulia et al. (2019) analyzed the viability of the medical package delivery business as an initial implementation of UAM services with a goal of achieving profitability within the first five years of operations. Their analysis showed that while projection of revenue does not occur until the eighth year of operations, the profitability reach shall shift within three to five years of operations because of the initial market capture and delivery prices. Similarly, Hasan (2019) conducted a market study on the viability of UAM for last-mile delivery, air-metro, and air-taxi within the next decade. The analysis projected the first profitable year of last-mile delivery would not occur earlier than 2030 due to high certification, infrastructure, and vehicle costs. In retrospect, air-metro is anticipated to start earning profits in 2028 at 130 million trips with continual growth into 2030 with 740 million expected operations. The most impactful variables are certification, number of vertiports, maintenance and energy costs, limited passenger capacities, and vehicle supply. The air-taxi service is not projected to be profitable within the next decade due to higher infrastructure needs and connectivity; although, it is expected to have demand in urban areas like Miami, New York City, San Francisco, etc. Comparing current and future progress efforts, full-scale operations for last-mile delivery are much more near-term with a time span of 2-5 years compared to air-metro/air-taxi with a timespan from five to over ten years. According to Canadian Advanced Air Mobility Consortium (CAAM) (2020b), a consortium of Canadian AAM stakeholders, the gross domestic product growth from AAM introduction in Canada should gradually rise over a 20-year period from around $250 million for its initial five years to over $860 million over the final five years (i.e., 2036-2040) for the first 20 years of operations. Respectively, the job market is expected to expand from just under 2,000 to almost 17,000 AAM job opportunities within the same span of 20 years. Such expansion would also benefit Canada's government as the tax revenues from the AAM market are expected to rise to almost $170 million over the final five years of the 20-year period.

This project's working package #1 (Bert et al., 2022) conducted an extensive study of UAM demand. Figure 1 presents the cumulative market revenue of the UAM market.

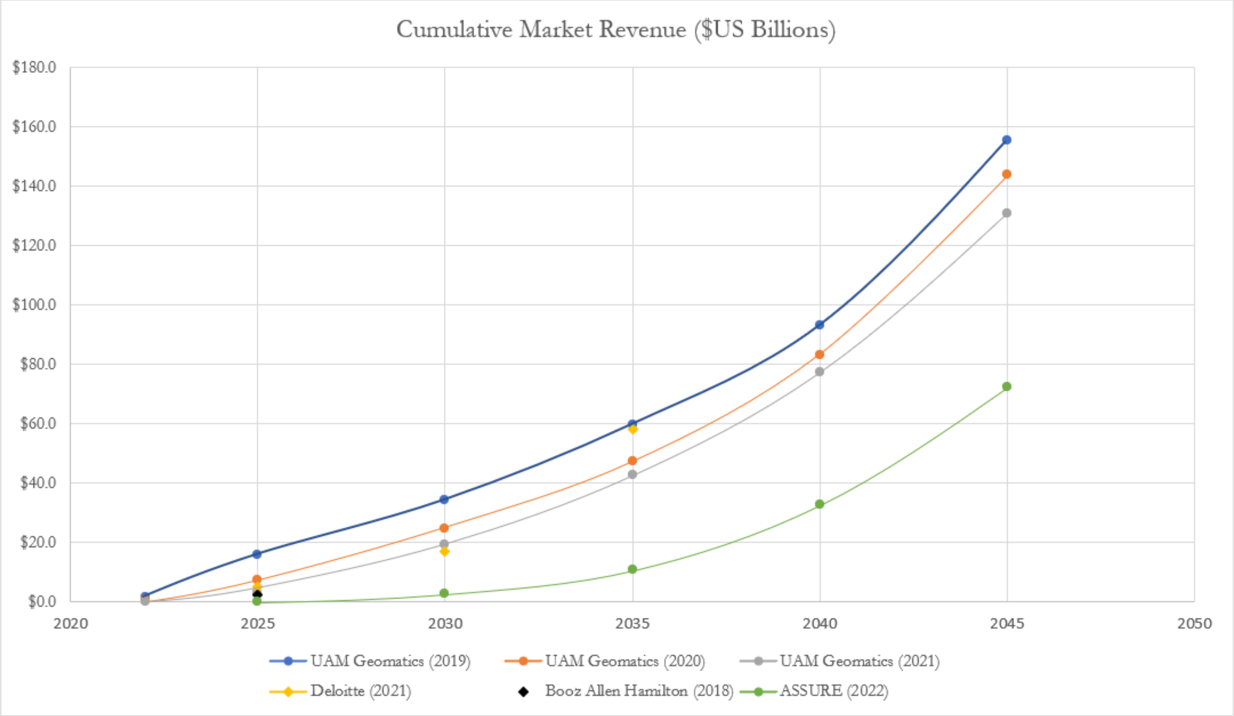


Figure 1. AAM US Passenger Market Revenue Projections Over Time (Revenue in $US Billions).

Morgan Stanley Research (2021) identified that the autonomous flying aircraft market is accelerating for the future of passenger travel, military and defense applications, and package transportation. The report projects a total addressable market of $1.5 trillion for autonomous aircraft by 2040. Flying cars (UAMs) with an ability to make four times as many trips as a regular car can also revolutionize the ride-sharing industry.

With the establishment of the AAM industry, supplemental projections for industry enabling rules and features also require attention. Wing and Levitt (2020) provided a timeline for the establishment of Digital Flight Rules (DFR) as a new set of flight rules adopted for UAM aircraft within the next three decades. By public consensus, the initial milestone would occur by 2025. Over the following decade, system specifications, performance requirements, regulations, and standards are expected to develop to support DFR implementation. The users should be able to build to the developed standards by 2040. The initial operational certifications and approvals would take place around 2045. Although the authors project full-scale maturity of DFR operations to emerge by 2050, the authors caution that new technology implementations take time within the NextGen framework to upkeep high levels of safety and security within NAS.

The UK Research and Innovation (UKRI) launched the future flight challenge, which is a £125 million program funded by the UK government and industry with the purpose of making the UK one of the leaders in the UAM sector (UKRI, 2021). The program includes five main stages:

1. Development stage. The main milestone of this stage is to develop and simulate the UAM services and to unlock the path for certifications and social acceptance.

2. Demonstration stage. This stage is scheduled to be accomplished by 2024, and the main purpose is to demonstrate the service in the real world, large scale, and integrate activities with strong socio-economic value impact.
3. Industrialization stage. This stage is planned to be achieved by 2026 and its main goal is to make the service more commercially viable and reduce the cost by increasing the production rate.
4. Scaling stage. Planned to be accomplished by 2028, the main objective of this stage is to scale the UAM service and make it more geographically distributed and available as demand and social acceptance increases.
5. Service-based stage. Expected to be accomplished by 2030, the main purpose of this stage is to fully integrate the services to provide rapid, seamless, and sustainable transport.

2.2 Minimum system, operational, and procedural requirements necessary to enable UAM integration

To consider UAM's influence on the NAS, the research team sought to identify the operational and procedural requirements necessary to integrate UAM.

2.2.1 UTM Constraints (Airspace, Flight Rules, and Data Sharing)

As a new entrant to NAS, AAM is projected to utilize significant chunks of pre-defined airspace, like small Unmanned Aircraft Systems (sUAS). But as sUAS operates in UTM airspace defined under 400 ft, UAM operations are expected to use a similar (or the same) structure for progressive and effective flight management. Like ATM, a concept of UAM Operational Environment (UOE) covers all UAM operations at once in low-level airspace, with consideration for various NAS constraints. While numerous studies outline specific UOE constraints, the environment will be established and managed by the FAA and other similar stakeholders. Therefore, only studies of comparable origin were reviewed in this section.

Hill et al. (2020), Patterson et al. (2021), and Volocopter (2021), based in Germany, gave a detailed explanation of how this concept is currently envisioned. According to these studies, the basic architecture of the UOE should be like that of the current UTM infrastructure plan, in which third-party federated service suppliers are in the scope of PSUs. This environment shall be the size of horizontal airspace between the top of UTM airspace and the bottom of regular controlled air traffic airspace. This coincided with an idea proposed by the CAAM (2020a, 2020b). They explained that low altitude airspace (ground to 400 ft) would be sUAS airspace, mid-level altitudes would be Urban ATM for UAM aircraft, and high altitude would be basic ATM. Multiple studies expressed different views on the Urban ATM altitudes and are reviewed later in this literature review. For example, according to Hill et al. (2020), the floor of a given UOE shall only hit the ground when necessary, in the case of vertiports and take-off and landing areas (TOLAs), to prevent interference with UTM airspace users. While UOE airspace is designed with UAM aircraft in mind, Hill et al. (2020) and Patterson et al. (2021) stated that conventional aircraft, such as general aviation (GA), should be able to enter the airspace if that aircraft can safely participate in traffic management and maintain appropriate separation. UAM aircraft would also be able to leave the UOE and fly in the NAS if that aircraft meets requirements for the airspace of operational intent, including equipment requirements. In January 2019, FAA selected three FAA UAS Test sites for tests and demonstrations in conjunction with the NASA and industry partners. UTM services demonstrated in UPP Phase One included: 1) the exchange of flight intent among operators, 2) the generation of notification to UAS operators regarding air and ground activities, known as UAS volume reservations (UVRs) and 3) the ability to share UVRs with stakeholders, including other UAS Service Suppliers (USS) and the Flight Information Management System (FIMS).

Within the UOE, the number of PSUs managing traffic may vary. Hill et al. (2020) and Patterson et al. (2021) outlined that, depending on the size of the UOE, one PSU may manage the whole UOE; though, if the UOE is larger, the volume may be divided into sectors, one for each PSU. The UOE should be flexible, meaning that portions of the operating area would be deemed “available” or “not available” based on factors like temporary flight restrictions, non-UAM users' needs, traffic demand, etc. For portions of the UOE within controlled airspace, especially within an airport area, the traffic management of UAM aircraft shall lie on the PSU in charge of the section with no active ATC management; the UAM aircraft should remain within the airspace designated for UAM operations. ATC can also close some or all portions of the UOE, as deemed necessary.

Routes with higher-than-normal demand, compared to other segments of the UOE, shall be designated as high-density routes. High-density routes would exist solely within the UOE and require more advanced capabilities for flight management. These routes would have access to more redundancy/emergency landing areas, as they are expected to be matched with aerodromes/vertiports utilizing appropriate infrastructure and capacity to support them. Since this designation is based on traffic demand, such routes shall be dynamic and negotiated by the FAA and other community stakeholders. For example, the dynamic attributes of high-density routes might involve being open during morning and evening “rush hours” or before and after sports events.

Since the route structure should be organized as a specific network, Zhu and Wei (2019) described two options for the network layout. Option one is a locally connected network with only certain aerodromes being inter-connected. This network is simple with fewer collision points within the routes; however, some flights may not have direct routing and would be forced to fly a zig-zagged path. Option two is a densely connected route network with direct paths between all aerodromes accessible to that environment. Even though this network has more direct routing, there is an increased safety hazard risk with more collision points. Covering routes and urban operational environment in general, McCarthy et al. (2020) proposed a layered structure for performance-based separation within UTM/UTM-like system. This structure would involve travel layers and deconfliction layers, serving the vertical separation function between each travel layer. The distance and duration of the planned trip would be used to determine the layer assignment for the flight. For example, shorter trips would be on the lowest layers, medium-length flights on middle layers, and long flights on highest levels.

To ensure a high level of safety on such routes, Rios et al. (2019) laid out a system of volumes. The operational flight volume is surrounded by the conformance volume to serve as a deconfliction layer and ensure adequate separation between the flights. Outside of the conformance volume is the airspace producing the operational data supplied by and for the PSUs/ USSs. If the aircraft breaches this conformance volume, the operation is flagged to be non-conforming. However, if the aircraft breached the conformance volume too many times or for too long, or if the aircraft breaches another operation volume, it would be flagged as rogue. Regarding volume and airspace conformance, Rios et al. (2018) proposed the Conformance Monitoring Service. This service would support UAM operators to ensure compliance related to their intended operational flight volumes. Alerts from the PSU/USS to the operator and from the PSU/USS to other PSU/USS are required when the flight leaves its conformance and operation volumes.

With the airspace structure somewhat laid out, Zapico et al. (2021) estimated the maximum airspace density for UAM throughput. According to the study, using single-passenger UAM operations with five-minute boarding intervals, the maximum airspace density at long-term cost was 540 aircraft/NM^2. For flights using a ridesharing concept with the same boarding intervals, the maximum airspace density was 444 aircraft/NM^2.

Data sharing for UTM aircraft ensures that all stakeholders are informed of UTM operations. According to studies by Volf (2017), Mueller et al. (2017), Ramasamy et al. (2017), Raju et al. (2018), Sacharny et al. (2020), and Rollo et al. (2017), UAS operators shall send operational intents and real-time information to USSs. The USS would then share primary constraints to public safety agencies, along with operational constraints, modifications, notifications, and other information to all the users. The data would also be exchanged with System Wide Information Management (SWIM) and supplemental data suppliers to include terrain, weather, surveillance, and performance information. The USS would send operational directives to the Flight Information Management System (FIMS). According to Dao (2019), FIMS serves as a bridge between the UTM ecosystem and the ATM system. The USS can identify and apply airspace usage restrictions through FIMS. It will send and receive NAS information regarding system impacts by using data exchange with ATM. SWIM will also share data feeds with FIMS. As FIMS, ATM, and SWIM are Air Navigation Service Provider (ANSP) responsibilities, the ANSP will provide constraints and directives considering NAS. The USS networks would define UAS mission constraints, operation boundaries, performance requirements, and distribution of no-fly zones, Notices to Airmen (NOTAMs), weather, etc. Lastly, UAM operators will provide position updates to the USS Network and ensure that UAM meets requirements for detect and avoid (DAA), planning, and obstacle avoidance capabilities. It should be noted that the testing requirements and integration challenges of UAM will differ from UTM such that an understanding of UTM does not necessarily lead to an understanding of UAM/AAM.

Regarding NAS constraints, Roche et al. (2018) argued that the USS accesses the ATM systems, made available via FIMS, to identify any NAS constraints or restrictions within the airspace during the intended flight times. If any exist, a fleet operator would see the information concerning these constraints and then alter their operational intent to ensure adequate pre-flight deconfliction. Both Roche et al. (2018) and Mueller et al. (2017) described that the FAA would issue dynamic restrictions under their authority to prohibit UAS use within that area. Authorized entities, such as law enforcement or fire departments, can submit a Dynamic Restriction Request for the FAA approval using USS or FIMS.

2.2.2 NAS Constraints

The NAS has grown and evolved for over a century, with growth in the volume and variety of air traffic on a yearly basis. As a result, an introduction of new entrants might be detrimental to maintaining airspace capacity in the vicinity of large metropolises and congested airports. The National Academies of Sciences, Engineering, and Medicine (2020) explained that the NAS has been continually growing and developing regardless of the growth patterns of aviation users.

Engaging both public and private sectors in arranging standards, resources, and capabilities for AAM development will be essential to the implementation and growth of that subset. Unmanned operations, such as those under UTM and later AAM, can influence NAS growth through the integration of ATM and UTM (later UAM/AAM) systems to promote safe non-segregated operations between all aviation users. Some of the integrated architectural requirements must include a defined framework with organized functions and interfaces, defined roles and responsibilities of new users, sufficient communications, room for future growth, and improvement of current safety policies. Comparing NAS constraints and UAM challenges to past, similar services (i.e., helicopter routes), Vascik et al. (2018b) identified NAS-dependent challenges that include weather restrictions, access to controlled airspace, autonomy interactions with ATC, and safety in congested flight areas. The main UAM impacts from these constraints were found to be on ATC scalability, all-weather operations, and network operations and development. The Autonomous Aircraft Ecosystem comprises of manufacturers of sensors, batteries, aircraft parts and software supporting the operations. UAM operations would not be able to comply with current airspace requirements, which would deteriorate the pace of growth. Factors like ATC clearances in Class B, weather constraints for Visual Flight Rules (VFR) operations, and altitude requirements, all impose limitations on AAM scalability. Air Traffic Control Association (2021) found a disconnect between the NAS platform of today and the one envisioned to emerge over time. Current NAS employs operations that are managed around military and commercial operations with static airspace structure and CNS capabilities. Whereas future NAS will incorporate services for all airspace users, switch to more performance-oriented airspace modeling, and include time and weather as supportive constraints to expand the flight environment.

As with any other new entrant, many assumptions have been applied to maintain efficiency of the operations for all users. FAA (2020a) assumes any developments of regulatory, operational, or technical background to satisfy safety concerns that may arise. In addition, UAM aircraft are expected to operate within the environment identified within NAS yet separated from other NAS users. UAM will have established corridor networks that allow safe passage for aircraft operationally separated from other NAS users. The data would be shared via FAA-NAS data exchange protocols to ensure clear connection and communication between the FAA and UAM community. While other users can access the corridors, they must comply with the performance and other requirements outlined for that environment. If for any reason a UAM aircraft leaves the defined corridor into the active NAS airspace, the same rules apply. Setting additional assumptions for airspace integration, Lascara et al. (2019) and Lacher (2020) anticipated that the new structure should not impose any safety risks on legacy NAS users or initiate many changes to NAS structure and operations. New equipment requirements or access limitations should neither jeopardize current low-level Instrument Flight Rules (IFR) and VFR traffic nor force substantial changes to ATC workload and ATM automation.

The ATC element, as a limiting human factor within the NAS structure, is one of the fastest variables to reach capacity. Hasan (2019) argues that UTM airspace integration in NAS/ATM presents the biggest challenge, yet it will be essential for UAM operations to extend above 400 ft above ground level (AGL), as well as for separation and obstacle avoidance purposes. The most challenging aspects of integration into NAS are low-altitude urban operations and VFR/IFR operations. All would require a well-developed UTM-ATM relationship to provide safety and be able to operate in dense controlled environments. Additional infrastructure and CNS capabilities will be beneficial to enable UAM flights. Vascik and Hansman (2017) identified ATC and communication equipment capacity to be the limiting factors to reaching higher UAM throughput in NAS. Analysis of airspace in Los Angeles and other major urban areas showed that much of the airspace is not utilized for commercial operations, GA, or helicopters. Safety buffers shall be likely be a critical feature to satisfy ATC's aversion to risk. Instead, it may be used for upscaled ODM operations without having any impact on the NAS. Vascik and Hansman (2020) also proposed the use of static and dynamic cutouts for airspace allocations to provide procedural separation to all air traffic based on the airspace usage and traffic flow patterns. The cutout availability will be defined by the ATC, but the operations within that airspace will not be under their control. Using the proposed concept has increased UAM accessibility by 80%, without imposing an extra workload on ATM infrastructure. Since many urban environments lie within or in the vicinity of airport airspaces (Class B, C, or D), Thipphavong et al. (2018) envisions UAM operations to operate within controlled NAS airspace with the condition of two-way ATC communication. Nguyen (2020) explained that the current state of the NAS would not be able to support the predicted UAM growth. On the other hand, the development of digital data communication will allow improved ATC automated decision support tools, trajectory-based operations, and Dynamic Delegated Corridors (DDCs) with improved Required Navigation Performance (RNP). In turn, it will promote the NAS's openness to a safe UAM environment. Stansbury et al. (2019) investigated the impact of UAS incidents/accidents on NAS performance and activities. The results showed that incidents during the approach phase did not have any irregular impact on any activities; however, during the cruise phase, it imposed uncertainty for ATC to control and divert traffic out of the UAS's way, with some disturbance during the approach phase. As per impact to other aviation stakeholders in general, the results showed only a 26% chance of having at least a medium to high impact on people or property on the ground.

More broadly, considering airspace in general, Gawdiak et al. (2012) compared and evaluated the functions of NextGen schedule optimization versus resource allocation within NAS for throughput, delay, and fuel efficiency. The results showed by using flight and schedule optimization techniques, the NAS could accommodate 25% more throughput, reduce the delay by 90%, and add over 10% to fuel efficiency. Using resource allocation, the NAS accommodated only 14% more throughput, increased delay by up to 105%, and improved fuel efficiency by 6%. Their results showed that applying modifications to flight scheduling and planning to optimize NAS usage allows maximum throughput, reduces delay, and increases fuel efficiency. Wing and Levitt (2020) defined that current IFR and VFR rules would bind UAM operations to certain conditions and limit operations beyond those conditions. The new concept of DFR permits operations in Instrument Meteorological Conditions (IMC) and Visual Meteorological Conditions (VMC) available to all airspace users. These rules should co-exist with IFR and VFR without imposing extra ATC workload yet enable new operational capabilities different from traditional flight rules. Their gradual implementation would enable automation features, new services with access and flexibility, and new CNS capabilities, which all provide a path toward non-segregated IFR/VFR/DFR operations. Lascara (2019) presented a very similar approach to define a new set of flight rules, Augmented Visual Flight Rules (AVFR), specified only for UAM operations that address the transition from pilot-based see-and-avoid capabilities to the unmanned analog, sense-and-avoid. The AVFR concept includes enhanced onboard automation and sense-and-avoid technologies to enable AVFR flight, but there ultimately should not be a difference in operational decision-making whether there is a Pilot in Command (PIC), Remote Pilot in Command (RPIC), or automation using AVFR. Considering that UAM operations are established within corridors, AVFR should not impose any risks to already existing IFR and VFR traffic. In addition, Mueller et al. (2017) recognized airspace capacity as a dynamic value, which can be possibly regulated by an automated system, depending on types of operations, time of the day, weather, aircraft capabilities, and traffic flows. To relieve stress from NAS, especially in congested environments, a mix of corridors and traffic flow management should be established to allow predictability and separation of operations. While it remains unlikely that a new airspace class would be identified, airspace regions and volumes can be identified for sole ODM use to maintain the capacity and demand.

To ensure efficient data flows between the UAM and UTM stakeholders and current NAS services, a platform must be established for data sharing. Even though the FAA has full authority over NAS activities, Patterson et al. (2021) predicts that it will delegate many responsibilities and functions to other stakeholders within the AAM community such as a PSU. Therefore, if the UAM aircraft stay within its designated UOE boundaries or corridors, they will be managed by UOE/Corridor stakeholders, i.e., PSUs, with minimal (if any) pressure on the ATC system. Weather services provided to commercial and GA might not be suitable for PSUs overseeing a UOE or corridor due to their geographical position over urban areas away from the airports. The weather systems and data will also be managed by third-party stakeholders to support UAM operations without the need to augment more of the NAS services. AAM/UAM weather can include challenges not encountered by traditional users such as urban canyons, which requires further study and be addressed by future augmentation of NAS services. Kopardekar et al. (2016) expects UAS operations to initially have almost no impact on the NAS as they would be segregated from other NAS operations. As technology advances, they would gradually be introduced to some NAS activities on some occasions as they extend into BVLOS. Once the automation and DAA systems reach maturity, UAS may be introduced into dense traffic NAS areas. Taking a similar approach from an ATC perspective, Rollo et al. (2017), Kopardekar et al. (2016), and Young et al. (2020) envision that once the UTM or a similar network is established, it would be connected to the FAA's SWIM platform for NAS data sharing as well as the ATC system to exchange the latest updates and information on NAS status and impacts. While Young (2020) also recognized that connectivity to SWIM would be essential for UAS aircraft operating in NAS, CNS was identified as one of the main drivers for full and deliberate operational integration. Ellis et al. (2020) analyzed In-time System-wide Safety Assurance (ISSA) to continuously analyze NAS data to predict emerging risks to UAM flights. ISSA would assess data, like ATC, weather, airports, etc., on a second-by-second, minute-by-minute, and hour-by-hour basis. However, the system only analyzes NAS constraints and does not include aircraft incidents or accidents. Roche et al. (2018) explained that FIMS will be used to share different NAS constraints to UTM participants in real-time. Information such as flight irregularities, airspace changes, incidents/accidents, or other NAS pertaining data shall be distributed among users and other stakeholders, especially those impacted by it. The FAA would also have the power to set dynamic airspace restrictions if the activity within that volume poses a safety hazard to UTM operations.

Communications, as part of UAM operations, are critical to NAS safety. Verma et al. (2020) described that, currently, UAM pilots would contact ATC before performing their operations in the existing NAS, which is inefficient for UAM demand. Increasing UAM aircraft efficiency by allowing aircraft with advanced technology to enter common airspaces without ATC communication also needs to maintain safe separation from traditional manned aircraft. Using the current helicopter routes as a reference, creating significant airspace for UAM operations would maintain the NAS's efficiency. When considering NAS part in ODM aviation, Antcliff et al. (2021) defined confining variables like onboard equipment, ATC, two-way communications, and weather. The communications part was identified as one of the limiting factors for the scalability of operations; however, ODM growth should expand with the development of proposed digital communications. Many technologies currently in development are not perceived to act just as an improvement but rather as an essential element of feasible operations.

Booz Allen Hamilton (2018a, 2018b) analyzed weather patterns in specific urban areas of interest to evaluate the barriers it may impose on UAM operations. The weather data sources that might be applicable for identifying hazards around urban environments are Meteorological Aerodrome Reports (METARs), vertical soundings from balloons, and Pilot Reports (PIREPs). The results showed significantly different weather patterns between multiple areas within the urban environment and between surface and aloft altitudes. Looking at results by geographic locations, weather patterns on the West Coast are more favorable for UAM flights than in the Central US or East Coast. Even though most of them showed high-temperature ranges during summertime, areas like Denver proved to be unfavorable for UAM operations due to the unpredictable weather patterns. Cities like New York and Washington, DC, recognized a significant impact from IFR weather and strong winds during most of the UAM operational time. Miami and Texas conditions imply many similarities, with frequent thunderstorms and low-level wind shear.

2.2.3 Altitudes

UAM flight operations depend upon the identification of viable altitudes to ensure safety of the UAM aircraft and other airspace users. A Booz Allen Hamilton (2018a) study considers a range of operational altitudes for UAM between 500 and 5,000 ft. The authors justified this range by their weather analysis and strong winds aloft at altitudes above 5,000 ft in the study's cities of focus. Vilar Llidó (2018) explains that to provide UAM services within urban environments, the operational altitudes must be defined in low-level airspace within Class G (uncontrolled). They state that, at least initially, UAM aircraft will be used only for VFR flights in the low-level airspace where the same obstruction clearance rules apply – 1000 ft vertically and 2000 ft horizontally. The expected cruising altitudes are set to be up to 5,500 ft. Chan et al. (2018) predicts that the initial UAM operations are expected to start in low-level airspace below 2,000 ft. Once all major characteristics of UAM operations are identified (i.e., services, procedures, support tools, etc.), such aircraft can be integrated at higher altitudes. Lascara et al. (2019) states that most operators expect the operating altitudes to be at or below 5,000 ft over metropolitan areas. sUAS as part of UTM operations will generally be bound to altitudes below 400 ft. Although, in their airspace integration concept, UAM aircraft flew through UTM corridors allocated under 2,000 ft (at around 1,700 ft).

Analyzing the impact of altitude requirements on airspace constructs, Hill et al. (2020) describes an airspace structure like the current NAS structure. The aircraft shall descend to the ground aerodromes within the upside-down cake airspace from their cruising levels of 1,500 to 4,000 ft. That approach/departure path will be restricted from sUAS since their operating altitudes are from the ground up to 400 ft. Similar approach/departure paths can exist for vertiport structures located on top of the buildings. Mueller et al. (2017) explains that UTM altitudes will separate sUAS and ODM-types of operations. sUAS aircraft are projected to operate in low-level uncontrolled airspace, typically below 700 ft. The proposed operational altitude range is between 400 ft and 700 ft. Unlike sUAS, ODM is expected to participate in the controlled airspace at altitudes between 1,000 ft and 3,000 ft. Upon further analysis of low-level airspace in major metropolitan areas with a purpose to localize safe operational altitudes, Vascick and Hansman (2017) found that currently proposed UAS operational blueprints are not usable for ODM procedures due to inefficient allocation of airspace and operational altitudes, little to no coordination with ATC, and longer integration timelines. Within their analysis of Los Angeles International Airport, only 5% out of 80% of all commercial flights utilized low-level airspace (under 2,500 ft), predominantly controlled by ATC. The analysis of other locations such as Boston, San Francisco, and New York City showed similar airspace utilization proportions. Therefore, they proposed to utilize that portion of airspace to promote the integration of ODM into the low-level altitudes by reducing separation requirements and new airspace allocations. As an extension of these findings, Vascik et al. (2018b) evaluated various flight constraints for three case studies for Dallas, Los Angeles, and Boston within their report. They found that the majority of UAM routing would lie at or below 3,000 ft AGL; although, it was also noted that longer cross-city routes may reach up to 6,000 ft AGL.

Airspace configuration within the simulation of UAM has been addressed by Rothfeld et al. (2018), where they found that an altitude of 1640 ft provided a reasonable level of safety for their simulation of UAM traffic over Sioux Falls. Though the scenario included three different altitudes – 820 ft, 1,640 ft, and 3,280 ft, the altitude choice depended on the aircraft speed and route length.

From the surveyed materials, the team observed that infrastructure developments used to support UAM aircraft and flights impact the operating altitudes considered. Patterson et al. (2018)'s analysis of density altitudes found 6,000 ft Mean Sea Level (MSL) to be the most optimal altitude for take-off and landing to operate on an average day in all locations (except Denver and Salt Lake City with only 99th percentile day). Although, the flights can be conducted with the density altitude requirement of 3,200 ft MSL only on the 95th percentile day in all locations but Denver, Salt Lake City, Las Vegas, and Phoenix. Further analysis of operational altitudes considered Title 14 of the Code of Federal Regulations (CFR) Part 91.119 separation requirements of 1,000 ft vertically and 2,000 ft horizontally of the highest obstruction. From the review of the tallest man-made structures, the investigators found most stood below 2,000 ft with only five that exceeded that limit by less than 100 ft. Considering the prescribed separation requirements, they determined cruising altitudes of 3,000 to 4,000 ft to be the most optimal to provide substantial separation in more dense operational areas. Bosson and Lauderdale (2018) considered vertiport versus cruising altitudes in their UAM Network Manager simulation case study for the Dallas metroplex. Within the scenario, the vertiports were located between 480 ft MSL and 1047 ft MSL in which Dallas Fort Worth International Airport (DFW)'s elevation at 607 ft MSL falls within that range. As a result, their software was programmed to assign altitudes well above the vertiports' elevations. For a single flight, the chosen cruise altitudes were 800 ft and 1,500 ft MSL. With three flights taking off and landing in the span of 15 minutes and two using the same vertiport, an altitude of 1,400 ft was assigned for spacing and sequencing.

Regarding CNS requirements and technological advances, Lin and Shao (2020) noted that the operational altitude depends on the level of surveillance used by the participating aircraft. In their study on the application of NAS-UTM integration principles to Taiwan airspace, they outlined that the operational altitudes for sUAS will be below 400 ft, and larger UAS aircraft (inclusive in scale to UAM systems) will be within 400 ft and FL180 (18,000 ft). Volf (2017) and Rollo (2017) have similar concepts of operations, where initial integration of UAS will be in the low-level airspace below 500 ft AGL due to absent requirements for ATC communications. Both studies concluded that future operations shall expand into the higher airspace with further development of technologies and growth in operations. Unlike other studies, Stouffer et al. (2020) provided recommendations to manufacturers that outline sensor design and DAA technologies necessary to meet flight in low-level airspace above and below 400 ft AGL. The study's assumed operating altitudes at or below 5,000 ft based on the current NASA UML-4 description and limiting large UAM vehicles to altitudes below 400 ft would amplify the occurrence of obstructions, affecting the quality of CNS signals and increasing the possibility of harm to people and property. Analyzing the tallest buildings in the US and the operability of electric vertical take-off and landing (eVTOL) aircraft, the hypothesis concluded that most optimal operational altitudes are at or around 1,000 ft to prolong battery life, avoid accidental damages from downwash, and provide the most efficient flight paths with two-way traffic.

2.2.4 Velocities

While not the most essential element of UAM/NAS integration requirements, aircraft speed plays a role in infrastructure establishment and general operability of UAM aircraft. Moore et al. (2013) defined a minimum cruise speed of 130 knots (kts) with a desire to increase its velocity for their concept of ODM operations. With current aviation technology, 130 kts is the maximum cruise speed for energy efficiency. It's predicted that electric aircraft altitude and cruise speed limits shall increase as better battery capacity emerges in the future. Similarly, Prevot (2020) assumes that aircraft will maintain a cruise speed of 120 kts with 2 NM in trail, which is roughly 1 minute. Booz Allen Hamilton (2018b) identified that UAM speed, along with its weight, service, power, and passenger amount, determines the extensiveness of the FAA's certification process. For example, an eVTOL's current cruise speed would fall in the range between 105-150 kts. A hybrid UAM aircraft would have a cruise speed range of 175-260 kts. Many aircraft design proposals, such as hybrid, conventional, and electric propulsion aircraft, are faster than traditional helicopters currently in service. Conventional aircraft have a cruise speed range of 35-115 kts, 35-165 kts for hybrid, and 95-165 kts for electric, while electric multirotor aircraft are the slowest with a range of 35-50 kts. The research also assumed a standard rate of climb of 500 ft/min.

Surveyed literature addressed the speeds flown relative to flight profile. Kotwicz et al. (2019) found that current electric aircraft with a range of up to 50 NM are most feasible with flight profile speeds of up to 150 kts. However, the continuous advancement of battery technology projects electric aircrafts' distance and speed capabilities to increase in the future. Niklaβ et al. (2020) estimated that UAM travel is much faster than traditional ground transportation regardless of take-off, landing, and turnaround periods. For evaluation of cruising speed, the simulations carried out used a cruising speed of 60 kts; though, low cruising speeds were outlined to be around 40 kts. Both Niklaβ et al. (2020) and Zapico et al. (2021) proposed speeds for different flight profiles depending on the environment. Standard vertical speeds were 500 ft/min for take-off and 300 ft/min for landing. Approach and departure speeds were 500 ft/min vertical and 45 to 130 kts horizontally (variations based on the environment landscape). Cruise speeds in all situations were 130 kts. Stall speed was identified to be 73 kts.

Both trip demand and flight planning are aspects of operations where velocity plays a fundamental role. In the attempt to examine the effect of speed variations on trip times (baseline is 81 kts), Rothfeld et al. (2018) found that there is a 29% increase in cruise time for 27 kts, 5% decrease for 135 kts, 8% decrease for 190 kts, and 11% decrease for 245 kts. Even though the cruise time decreases with an increase in cruise speed, the difference was not large enough to indicate a significant relationship. Patterson et al. (2018) did not define a specific cruise speed to account for various aircraft designs with different tactics for range maximization. The aircraft must be able to climb at least 500 ft/min during the cruising segment. In addition, cruise speed was found to be influential for flight planning purposes, particularly fuel/battery reserve estimations. Nevertheless, UAM networks can have a required minimum cruise speed for aircraft service during rush hours despite the design varieties. Lascara et al. (2019) stated that multiple UAM operators expect corridors to sustain speeds of up to 150 kts. Although, speed as a performance variable will play a decisive role in enabling capabilities that might necessitate higher aircraft performance (e.g., corridor availability). Looking at the demand perspective, Hasan (2019) found that most consumers were willing to pay more if the UAM trip or UAS delivery was either more imminent or faster. With their assumed cruise speed for UAM aircraft of 130 kts, UAM operators are better capable of attaining the desired shorter flight times. On the contrary, Hann et al. (2021) designed two scenarios to determine the effect of speed on the demand for UAM aircraft: a low-performance aircraft with a 30-mile range, 110 kts cruising speed, low hourly operating rates, versus a high-performance aircraft with a 90-mile range, 150 kts cruising speed, double hourly operating rates. Their results showed pricing to be the deciding factor for traveler choice as more demand was generated for low-performance aircraft.

Looking at speed benefits for UAM, Thipphavong et al. (2018) found that UAM aircraft exceed expectations for the speed of transporting people and cargo compared to current ground and air transportation systems, with the addition of take-off, landing, and transition procedures. Depending on the design, some aircraft may not be able to hover for too long but can fly at faster speeds, and vice versa. UAM CONOPs must consider such UAM aircraft's performance differences since their cruise speeds range from about 70 kts to over 200 kts.

2.2.5 Automation

The use of automation for UAM remains a controversial topic within the AAM community. CAAM (2020a) and CAAM (2020b) argue that while current eVTOL aircraft require a human pilot for operations, the aviation industry will see an increase in automation in the next 20 years. Goals of integrating automated aircraft into UAM include reduced demand, costs, and fewer errors by human pilots. Additionally, it is anticipated that a workforce shortage of qualified AAM/UAM pilots as the scale of operations increases and due to anticipated certification requirements, training, and salary of onboard pilots. Near-term, the industry desires automated aircraft to be safer than piloted aircraft. Volocopter (2021) predicts a gradual introduction as the operations expand by developing an entire AAM ecosystem which includes aircraft, ground infrastructure, and ATM Systems. By eliminating the flight crew, UAM will become more affordable, safer, and a greater opportunity for expansion within the industry. Without automation, as the number of aircraft increases, pilot workload would increase, especially in unpredictable environments (e.g., urban airspace). Regulations and public acceptance challenge the industry's goals of increasing and improving automation technologies. The transition to more automated systems shall progress cautiously, requiring minimally automated operations and flight planning to be initially established via piloted operations.

Enablers of UAM automation should be carefully considered, including infrastructure, equipment, and general technological development. NASA (2020b) proposed automated vertiport system to implement ground services, departures and arrivals, and safely commencing passengers or cargo. This system uses CNS principles to support UTM, PSU networks, and other vertiport assimilation. The vertiport is automated by the fleet operator's Operation Control Center (OCC)'s inputs to perform UAM vehicle movements, receive flight data, or calibrate aircraft systems. Automated vertiport and regional vehicle supervision systems will regulate arrivals and departures within the airspace for both piloted and non-piloted operations.

The Northeast UAS Airspace Integration Research Alliance (NUAIR) plans automation of UAM in their High-Density Automated Vertiport CONOPs using a Vertiport Automation System (VAS) (NUAIR, 2021). The VAS is broken up into several subsystems: Supplemental Data Service Provider (SDSP), Resource Management and Scheduling Service (RMSS), Vertiport Manager Display, Surface Trajectory Service, Aircraft Conformance Monitor, Risk Assessment and Hazard Identification, alongside other out of scope subsystems. The SDSP works as a communication hub for vertiport-vertiport and UAM operator-vertiport communication to safely convey the status of flights between vertiports. RMSS works to manage aircraft at the vertiport by enforcing vertiport rules and regulations, while managing the charging, fueling, loading, and taxi of the aircraft along with other ground-based services. The RMSS is also in charge of communicating with PSUs for flight management through the SDSP. The Vertiport Management Display acts as a way for a user to step in and stop automation during off-nominal conditions of ground-to-air and air-to-ground operations. The Surface Trajectory Service oversees taking data from the RMSS and communicating taxi routes, gate availability, and other necessities for safe aircraft movement within the vertiport. The Aircraft Conformance Monitor, Risk Assessment and Hazard Identification services work together to identify hazards in and around the vertiport to provide the best plan of action for safe conduct of operations. All these systems must communicate with one another and with the human element to guarantee safe operation of the vertiport and UAM services. Several articles reviewed and addressed the integration of onboard automation to UAM vehicles. Goodrich (2020) presented NASA's proposal of an Automated Flight and Contingency Management (AFCM) system for UAM operations. While a fraction of it is integrated within the aircraft via strategic and tactical interfaces enabling auto-flight through flight and propulsion control, all other components must be integrated within airspace and operations via mission management, strategic flight path management, and tactical operations. As per UAM operations support, Bosson and Lauderdale (2018) evaluated NASA's software AutoResolver to incorporate automation into the concept of Sequencing, Scheduling, and Separation (SSS). The results show that when the base standards of SSS are reduced, AutoResolver could accept the change and either eliminate or successfully resolve separation losses and other conflicts without creating new ones. For this reason, the software can be used for future UAM integration purposes even with current strategic and tactical capabilities to ensure the safety and efficiency of UAM networks. Exploring UTM requirements, McCarthy et al. (2020) recognized that developing an automated UTM system with a wide range of capabilities, including flight planning, deconfliction, path optimization, etc., applicable to any urban environment remains a challenge for UAS integration into NAS. In their opinion, if a human is taken out of the loop, the system should consider all inputs and data to analyze and provide the optimization and real-time deconfliction, creating a safer environment all at once.

The literature review examined operational assumptions of UAM influenced by automation. Vilar Llidó (2018) argues that more automation enables more users without advanced aeronautical knowledge/training to operate them. On the other hand, they note that greater automation requires more onboard equipment, which leads to an increase in aircraft weight. Increased aircraft weight can adversely impact the operational performance of lightweight aircraft. Despite that, initial operations shall require certified pilots as the UAM operations are expected to begin with VFR. Assuming UML-4 integration, Hill et al. (2020) evaluated automation responsibilities for three operational scenarios, one onboard PIC, RPIC responsible for one aircraft, and RPIC responsible for more than one aircraft, across various factors, such as mission and flight path management, tactical operations, aircraft control, etc. Across all three scenario variations, automation maintained primary responsibility for most of those factors except tactical operations. Analysis of tactical operations showed a shift of responsibility for detection of hazard from primary to full when the PIC was no longer onboard, as well as a shift of responsibilities for maneuvers and hazard mitigation from secondary to primary for the same reasons. Looking at automation integration within the UAM paradigm, aircraft development and production would use automation for avionics, data transmission, and other onboard systems. Individual aircraft management and operations may use automation for faster decision-making, as well as during contingency situations with little to no supervision. Within airspace system design and implementation, automation would apply for separation and sequencing within corridors with eventual scheduling of operations. For airspace and fleet operations management, automation may be used for Vehicle-to-Vehicle (V2V) information exchange and strategic deconfliction.

The human element or the absence thereof must be considered as it can be both beneficial and/or a challenge. Loon (2020) asserts a human on the loop must remain an element of aircraft operations, regardless of the level of aircraft automation. While automation systems shall create and perform flight plans, human supervisors will analyze irregularities and arrange limits and priorities for automated aircraft to enhance safety. Aircraft automation would reduce human pilot fatigue and error, which also decreases the chance of accidents. Nevertheless, the UAM's software applications can assist in avoiding potential conflicts as human limitations may impact situational awareness.

NASA (2020a) described the gradual elimination of humans from within-the-loop to on-the-loop to over-the-loop. As automation matures, the human element goes from receiving all the data and making decisions to a rather supervisory role. The last step of automation independence is when the human element acts only when necessary or if the automation advises doing so. Like Hill et al. (2020), Moore et al. (2013) recognized the same three operational scenarios for automation integration for ODM. However, they explained that taking out a human element from the aircraft does not eliminate human error during the design process. While proper automation responses can be designed for standard (predictable) contingency scenarios, it is much harder to develop responses that tackle unpredictable events or combinations of such. To do that, automation should achieve a much higher, almost human-comparable, level of intelligence to ensure the safety of pilotless operations. Outlining the pros and cons of each scenario, adding more automation typically added more disadvantages than advantages due to hardware requirements, vehicle certification and regulations, development risks, ground support, reduced flexibility, public acceptance. On the contrary, Ellis et al. (2020) assumed vehicle autonomy to be the standard of a low-altitude urban environment. However, the main consideration for achieving that autonomy is the trust between a human and automation. While close human supervision and contingency management would be necessary at first, automation can be scaled up using machine learning to the level of advanced prediction to surpass human performance. The authors described these events as automation surprise – an occurrence where automation predicts and anticipates a situation without human understanding or awareness of the circumstances. Therefore, trust between the system and a human should be established prior to the emergence of higher levels of automation. Taking the perspective of a pilot as a resource, Antcliff et al. (2021) described autonomous capabilities to influence UAM operational environments by reducing the negative impact of a pilot on the operations, increasing the pilot shortage with the growth of UAM, and improving the feasibility of passenger-carrying flights. They explained that pilot resource is one of the most growth-hindering aspects of UAM development, and thus, by eliminating it, automation would allow much faster growth of this industry. Discussing the safety of autonomous aircraft, initial operations are projected to be cargo only; however, over time, coupled oversight from safety stakeholders and the FAA is expected to prove a high safety threshold of the operations.

With automation integrated into multiple domains of UAM operations, certain requirements shall emerge to protect the safety of operations. Ramasamy et al. (2016a) summarized that automation should be capable of decision-making functions to include strategical, tactical, and emergency flight planning, conflict detection, avoidance, and resolution, as well as avoidance of terrain, weather, and other hazardous phenomena. In follow-on research, Ramasamy et al. (2017) defined that the safety of UAS integration depends on the automation functionality and standards for human-in-the-loop interfaces. UTM services should be based on automaticity, autonomy, and autonomous operations, which additionally include self-configuration, self-optimization, self-protection, and self-healing. The human element shall be largely eliminated from operations but remain essential to maintaining UTM goals and overall direction of automation development. In retrospect, Stouffer et al. (2020) explained that automation is usually the limiting factor for flight operations, especially during a landing phase, as it has excessive certification and operational requirements. Compared to current auto-land capabilities enabling complete landing with human supervision, most UAM aircraft would not be gliding into the runway environment but rather perform a three-dimensional soft landing on a small landing area (i.e., vertiport). As previously mentioned, introduction of automation for UAM operations shall likely entail more complex and vigorous requirements for automation and possibly other systems, as it has been seen within the industry. While auto-land provides benefit to the landing phase of flight, Cotton (2020) argues that autonomous UAM operations would need much more automated support for the whole duration of the flight. CNS technologies and their limitations inhibit the establishment of UAM autonomy. Like Moore et al. (2013), Cotton (2020) recognized the need for a much higher level of autonomy intelligence, i.e., more human-like, enabling more complex capabilities, such as conflict avoidance and resolution. Automation appears to be a strong enabler of UAM flight demand as prices are expected to decrease by removing the pilot element. Like Ancliff et al. (2021), this study proposes prioritization of automation for cargo flights to collect the data necessary to enable automated passenger transport in the future.

Despite the literature largely reporting automation as a UAM enabler, the survey identified some issues worthy of consideration. Hasan (2019) envisions UAM systems to eventually overcome the need for a human pilot for operations, reducing human errors, even though. Current NAS regulations generally do not satisfy UAM requirements for automated flight, limiting them to solely VFR operations. ATM automation will be another enabler for UAM operations as such technologies become more integrated within the NAS. Automated aircraft must allow onboard pilots, remote pilots, air traffic controllers, and mission control interactions in case of emergencies, regardless of the automation level. The National Academies of Sciences, Engineering, and Medicine (2020) state that automated aircraft systems must go through rigorous testing in low-risk environments before larger-scale implementation to prevent disruptions from common safety issues associated with automation. While the current advancements within NAS did not anticipate greater levels of automation in use, new automation-tailored operations and procedures can enable an easier integration of automated aircraft systems. Aircraft separation represents one capability significantly lacking within UAM automation due to the absence of suitable DAA technologies. Existing solutions augment separate airspace for automated operations, especially over rural areas, which will bring further improvement and acceptance of automated technologies. On the positive side, automation would reduce the chances of human error for upscaled NAS activities. However, a successful computer system replacing the human interface requires engineering, human factors, and other considerations, which all take time and industry support.

While many studies focused on current automation requirements and issues, some looked further to give a better outlook. Lineberger et al. (2021) expect piloted UAM operations to pave the way for higher automation levels. Within their study, 82% of study participants expect fully operable automated UAM to occur by 2042. Until then, the FAA should keep updating policies and certifications related to automation to meet the demand for automated UAM aircraft. Atkins (2021) explains six different automation functions:

- Perceive (via sensor fusions),
- Analyze and decide (via inner-loop control and flight planning),
- Warn/inform (via failure recognition),
- Act (via flight control),
- Limit (via aversion of unsafe acts), and
- Integrate (via inter-device automation integration).

For example, consider the following case. The UML-2 level of automation would be rather assistive for local separation assurance, collision avoidance, flight data recording, etc. However, expectations for UML-4 level include automation that functions more collaboratively with dynamic aircraft routing, airspace allocation, “co-pilot” functions, and contingency management with auto-land functionality. Considering automation capabilities coming in phases, Morgan Stanley Research (2021) outlined five phases. At the first level, introducing automation to UAM, the aircraft travel using certain automated features in the forms of autopilot and navigation using a Global Positioning System (GPS) or navaids, while sUAS get upgraded to more airspace functionality from simple VLOS. At the second level, automation controls most activities with pilot intervention as necessary, while sUAS and their enabling technologies mature in low altitudes using ground-based systems to coordinate manned and unmanned traffic. At level three, automation controls the entirety of the flight, but pilots intervene when specific performance requirements or capabilities cannot be met, while sUAS separation standards evolve to allow operations in the proximity of airports. At level four, there are supervisors with access to automated prediction tools that coordinate all UAM activities between each other rather than using pilot resources, while sUAS reach the capability of flying in coordination with each other in larger fleets. At level five, full automation is reached where both UAM and sUAS co-exist in urban environments with full certification to operate in any conditions.

2.2.6 Regulations

As the AAM domain is an emerging concept, there are no regulatory requirements currently set for UAM operations. Even though that problem is ongoing, some studies slightly touched on what regulations are expected to develop. Multiple studies, including Hill et al. (2020), Hasan (2019), and Hall (2020), state that the FAA will be the primary federal regulator of UAM operations, as its main goal is to ensure safety in the aviation field. Other federal agencies, such as the Federal Communications Committee (FCC) and Environmental Protection Agency (EPA), are expected to work jointly with the FAA to regulate portions of UAM operations under their jurisdiction. While the FAA remains the regulatory and operational authority for airspace and traffic operations, PSUs would maintain the responsibility for delivering flight-planning services, communications, and separation, among other data elements. Local governments can set ordinances that address issues not preempted by federal law and regulate the nature of UAM use such as zoning, noise, and privacy. These governments can also control the progress of the UAM market through business licensing and safety inspections, areas not covered by the FAA. One of such examples is inspections completed by the fire marshal. Hall (2020) added that insurance companies may apply their conditions and restrictions not already covered by a federal agency or locality.

These studies, as well as Lineberger (2021), agreed that some regulations may need to be created or modified to accommodate UAM limitations and spacing/separation needs. In addition, Hasan (2019) explained that air metro and air taxi operations are closely paralleled by regulations covering rotorcraft. Additionally, adding electric propulsion and autonomy to the NAS would require countless modifications within existing regulations, as well as the need to introduce new regulations to govern these aircraft and procedures. According to Booz Allen Hamilton (2018), air ambulances will require further evaluation due to the requirements for air ambulance procedures and specific portions of the operator's General Operations Manual. As UAM aircraft are expected to enter multiple segments of various aviation markets, gaps in current certifications demonstrate that new standards will need to be developed with a concentration in system redundancy and failure management. For more information on UAM regulations for aircraft certification, please review this project’s Working Package #2 technical report (Olivares, 2022).

2.3 Communication, Navigation, and Surveillance requirements and best practices necessary for UAM integration

To ensure safe integration of UAM into the airspace shared with or adjacent to non-UAM air traffic, the CNS requirements of the UAM system must be considered to ensure the aircraft remains within their assigned air volume along the prescribed flight plan/schedule.

2.3.1 Communications

Of CNS-related subsystems, communication systems have great diversity when considering the number of stakeholders, types of communication required to enable UAM, and the architecture of the communication system(s) for the UAM operating environment and the aircraft itself. Talking about general operational principles, CAAM (2020) stated that advancing the current aviation communication system would allow UAS aircraft, including UAM, to take operations from VLOS to BVLOS. National Academies of Sciences, Engineering, and Medicine (2020) explains that advanced aviation technology will require newer communication practices since current approaches don't support the upgraded communication systems. While introducing various communication design ideas to participating committees, various perspectives, physical barriers, and social barriers challenge the best communication strategy. As an example, Thipphavong et al. (2018) states that while voice communications will remain to be generally applicable, UAM communication links will be determined by the type and purpose of the mission the aircraft performs. IP networks can be used to provide aircraft and location data to PSUs and other UAM aircraft. However, UAM operators can always use verbal communication in case of a hazard, such as a loss of Command and Control (C2) communication link or degraded quality of service. UAM operations have various communications barriers requiring solutions for high-density operations. Data communication methods and standards must be established to communicate at vertiports, and with PSU, fleet operators, flight crews and aircrafts. Data models are used such as Aeronautical Information Exchange Model (AIXM), the Weather Information Exchange Model (WXXM), and the Flight Information Exchange Model (FIXM) along with flight and flow information.

Data sharing via links between all the various stakeholders remains a critical consideration for UAM operations. Hill (2020) states that PSUs will share information with other UAM operators and the FAA about their operational intent, airspace limitations, and other essential information. PSUs can also coordinate with each other to ensure safety during pre-authorized operations within the network. The FAA will use FIMS to alert UAM aircraft, fleet operators, and PSUs of airspace updates and provide recommended accommodations for flight planning. Even though ATC communications are not necessary during regular operations within corridors, UAM aircraft shall have the capabilities to do so for safety purposes. UAM pilots may also contact PSUs (via air-to-ground or ground-to-ground links) and other UAM aircraft (via V2V links) to transfer necessary information while at a hub-type vertiport, departing and arriving, and/or en-route. Similarly, Roche et al. (2018) expects communications to be primarily relayed through a network of automated interfaces between the FAA, UAM operators, and stakeholders. Ground Control Stations (GCSs) are capable of long-distance transmission support and UAM can maintain V2V communication, improving quality of communications, enabling greater UAM capabilities, and maintaining safety. Considering UTM as a similar system enabling UAS operations, UAS can exchange flight data with other aircraft, both unmanned and manned. Rios et al. (2019) discuss that USS must communicate any new or altered operations via the USS network to all other USSs that are using the airspace. USS operators must utilize UAS Reports (UREPs) to report meteorological and airspace traffic experiences to other USS pilots to avoid any risks or hazards. This system requires operators to follow a prioritization method, negotiate with other operators, and attain authorizations. Raju et al. (2018) analyzed FIMS, where USS can report intentions, messages, and locations and receive notifications about UTM airspace and operations. Similarly described in Hill (2020), this system allows UAM to operate without ATC clearance but enables ATC communications in case of deviations from authorized procedures. In addition, Lascara et al. (2019) foresees that UAM aircraft should be able to communicate vital safety procedures, which include traffic location, DDC updates, weather data, obstacles, flight paths, and destination information. For this reason, FIMS within the UTM system might be used as the main application for data sharing between different stakeholders. FAA (2020a) states that while PSUs are the primary communication method for UAM operators, ATC can communicate with the UAM community when it doesn't increase their workload. When working with UAM aircraft, ATC can set corridor availability, give updates about UAM procedures, acknowledge abnormal UAM performances, and review data from UAM procedures. From the European perspective, Kleczatský et al. (2020) explains that ANSPs will be responsible for air traffic supervision, Air Traffic Service (ATS), and broadcasting, while U-Space Service Suppliers will be responsible for communications with drone operators, pilots, and sUAS. U-space system, in general, requires constant communication between the users and stakeholders, as it is the basis for safe operations.

The equipment and means implementing the communication link must also be considered when addressing aspects of UAM communication. Stith and Khangura (2020) argue that upgrading current C2 systems is necessary for UAM integration, as such operations upscale. Different communication design ideas for BVLOS low altitude flights, such as 5G, radio, and satellite communication, are being evaluated to determine the most reliable communication method. These upgrades would also require special control facilities as newer aircraft increase their airspace usage. Taking it a step further, Stouffer et al. (2020) analyzed various proposed communication styles that are being considered for use to meet UAM aircraft demands. VDL Mode 3 was found to have the most appropriate frequency range and FAA approval. While Satellite 5G needs latency improvements to fulfill UAM intentions, Cellular 5G needs to improve signal prioritization, market case, and antenna directions. As a commercial technology, Low Earth Orbit (LEO) satellites may offer communication and navigation features at the same time. C Band for C2 is also an option; however, further research is needed to examine whether it can sustain UAS and UAM operations. UAM will use digital communication means during their operations, allowing vehicles to exchange aircraft data, including flight paths, to operators and stakeholders without traditional voice interactions. Ramasamy et al. (2016a) discuss that line of sight (LOS) and beyond line of sight (BLOS) communications will use voice, data, network radio, and/or satellite communication methods for air-to-air, air-to-ground, and ground-to-ground exchanges. Their research used Telecommunications Datalinks, Controller Pilot Data Link Communications (CPDLC), and Voice Communications. Liu et al. (2021) argue that C2 enables a wide variety of functions, but to meet them, it must have modest data rates, low latency, good communication range, high reliability, and high security. Newer air-ground communication means, such as Wi-Fi, WiMAX, Zigbee, Bluetooth, Cellular, and LoRa, are emerging to satisfy the UAM and UAS aircraft requirements as there is an issue of jamming or spoofing with the legacy C2. BVLOS C2 links may utilize satellite connections when UAS and UAM aircraft operate in remote or low-coverage areas. For example, LEO satellites provide more robust and faster signals than geostationary and medium earth orbit satellites. Lin and Shao (2020) suggested that UAVs will utilize 4G/LTE, LoRa, and Automatic Packet Reporting System (APRS) since they are like Automatic Dependent Surveillance – Broadcast (ADS-B) communication. These three systems are excellent for UAM operations since they can operate up to 400 ft AGL. Regional UTM (RUTM) operators may use verbal communication in the case of UAM conflicts. RUTM and UAM operators will abide by

International Civil Aviation Organization (ICAO) procedures on prioritization and avoidance methods. Kahne and Frolow (1996) suggested Aeronautical Telecommunication Network (ATN) or similar technology to be most feasible for operations, such as UAM, since communication links include the aircraft, operating centers, and traffic control facilities. This system's capabilities coincide with the proposal from other sources for a network of UAM operators, PSUs, and control facilities maintaining inter-communications. Hunter and Wei (2019) argued that sUAS require advanced technologies, such as Global Navigation Satellite System (GNSS), ADS-B, cellular communications (LTE/5G), and additional C2 links, for safe and reliable operations. LTE/5G improvements can deliver time- and frequency-based information at speeds desirable for sUAS operations while providing high reliability and outweighing the related costs. An airspace structure provides a potential mitigation on the demand of communication links throughout sUAS operations.

A potential strategy for UAM advancement would be the introduction of automation to the communications aspect of CNS. Vilar Llidó (2018) described that SSS techniques used by ATC today can be transferred to automation and the PSU networks, where the communications between aircraft will rely on surveillance systems and data sharing. Young et al. (2020) project UAM communications to utilize information-upon-request type design, where operators would request the most up-to-date information from service providers before the flight. The pre-flight information would be automated if operations are contract-based. UAM PIC would have minimal conversations with service providers during the flight and mainly use the UAM aircraft’s systems to convey data to the service provider. Some recommendations include a combination of GCSs and USS functions, USS/Supplemental Data Service Provider (SDSP) connectivity, and direct USS-to-vehicle communications during flights for more imminent data exchange while the UAM is still in-flight. Cotton (2020) explains that if controller-to-vehicle communications become more automated without actual remote PIC, the controller automatically becomes the monitoring remote PIC. By doing so, ATC communications would be limited to only the provided flight plan which prevents any changes or supplemental information about the mission and intentions. Suitable UAM communication methods, like Data Comm, ensure centralized surveillance and help to simplify data exchange. The communication design must provide flight information, means of control to operators, current and forecast data to ATC, as well as aid in conflict resolution. A communication link like Automatic Dependent Surveillance – Re-broadcast (ADS-R) can send and receive aircraft intent, making it cost- and time-efficient. In addition, various communication networks should receive weather and surveillance information and allow inter-vehicle communications, vertiport traffic management, and geofencing applications.

While considering UAM communications, it is vital to highlight V2V communications as a potential network topology. Volf (2017) described V2V and Inter-USS communications, highlighting the issues of UAS integration related to communications. V2V communications should satisfy flight coordination, DAA, and collision avoidance to ensure safe and reliable operation. Inter-USS communication replicates handover procedures like the current ATC system, as well as it regulates the ATC workload. However, some of the outlined issues were the unknown extent of Pilot-ATC communications and the quality of the C2 data link. Mueller et al. (2017) argue that sophisticated communication methods will reduce aircraft’s need for sensors, algorithms, displays, and other flight hardware, except for backup systems. Robust interaction designs will also allow improved aircraft supervision and operation automation wherever necessary. Emerging V2V communications shall enable communication of a better operating picture for an aircraft's flight path and intent via data sharing to other aircraft operating in the airspace.

Outlining the issues related to UAM communications, Stansbury et al. (2019) ran multiple scenarios with variations in occurring failures during UAS operations, including communications. Results showed a complete loss of the aircraft/crash within all three phases of flight – departure, mission, and arrival. The results indicate the need to include more communication procedures for UAS operations, such as computer-voice and text-to-speech systems, since the operators can utilize ATC services when necessary. On the other hand, Rollo et al. (2017) assume that communication links for ATC-PIC exchanges should resolve delays and poor signal quality. Simulations with PIC in the cockpit should aid in defining the maximum acceptable delay within those links. The purpose of the communication layer in UTM is to regulate information flows between UAS operators, USS, ANSP, and other users, create multiple ways of communication, investigate transmission delays, etc.

2.3.2 Navigation

The navigation aspect of the CNS systems is fundamental for the definition of operational environments, airspace throughput, and UAM aircraft navigational requirements. While FAA (2020a) does not indicate a specific means for the navigation of UAM aircraft, the authors explain that such operations are expected to follow a pre-defined system of routes (corridors). The navigation responsibility lies on the PIC to follow the submitted operational intent and established routing paths. Mueller et al. (2017) state that to meet advanced navigational performance for UAM operations, such aircraft are likely to be equipped with a Wide Area Augmentation System (WAAS)–enabled GPS. Lascara et al. (2019) explain that performance-based operations are essential for UAM flights within corridors and the UTM/UTM-like network in general. Since access to a corridor requires a certain level of navigational precision, better operational performance permits more direct routing and a wider variety of corridor options to UAM aircraft.

While considering UAM operations, it is important to explore the navigational practices used for UAS and sUAS aircraft. Liu et al. (2021) project that aircraft navigational and performance capabilities will be essential for acquiring permission to enter the airspace. Since geofencing is one of the features that will be used to prevent UAS from flying into restricted areas within UTM, they need to have a certain level of navigation capabilities to maneuver around them. Integration of multiple GNSS technologies could serve as one possible approach for navigational compliance. Pongsakornsathien et al. (2020) assumed GNSS for navigational purposes within their study for UAS allocated airspace, even though issues with its inaccuracy and dependence on receiver antennas were outlined. Nonetheless, the availability of major CNS principles used for UAS operations relies on GNSS access and the platform it offers.

To enable UAM aircraft with the appropriate navigational equipment and performance, the UTM or UTM-like system should be able to accommodate such capabilities. Ramasamy et al. (2016a) and Ramasamy et al. (2016b) outline the navigational functions of the New Generation Flight Management System (NG-FMS) to include a variety of navigation modes, radio navigation with manual and auto selection, Inertial Reference System (IRS), as well as an array of different GNSS features. Both studies outline 4D trajectory-based planning and optimization as the future CNS technology that relies on a navigation database, aircraft performance, and other related data. Such technologies will be based on the current GNSS equipage and other navigation sensors. Sengupta et al. (n.d.) proposed a concept of operations within the San Francisco Bay area where UAM aircraft travel from vertiport to vertiport following a system of waypoints and predefined traffic routing. Ginn (2019) provided a similar approach to UAM operations, adding conventional path approach blueprints, with the considerations for glidepath, fixes, wind, elevations, etc. Li et al. (2021) explored the viability of ground-based antennas used for CNS functions in areas with terrain in terms of providing enough coverage. They found that using their model, based on the spatial index, elevation, operational distance, and terrain, is feasible for projecting and simulating coverage of ground-based antennas for future CNS networks.

Once the system can support a variety of navigational means, UAM aircraft need to have specific navigational equipment onboard the aircraft to maintain high accuracy. Hill (2020) recognizes that UAM aircraft shall be capable of navigation using precise Performance-Based Navigation (PBN) capabilities to support flights in non-VMC conditions. An external data feed and onboard hardware, software, etc., will enable these capabilities. More stringent requirements for UAM PBN are predicated by obstacle avoidance, conformance to the routing, and emergency scenarios. A UAM PBN method would also be beneficial for take-off and landing procedures, as the crews would not need to be educated on multiple options of approaches (e.g., Localizer or Area Navigation (RNAV)). Vilar Llidó (2018) proposes using GPS for both navigation and active geofencing. Combined with a transponder, this will not only allow building and navigating the most optimal flight route considering restricted areas but also account for dense traffic areas. Like Pongsakornsathien et al. (2020) and in continuation of Ramasamy et al. (2016a, 2016b), Ramasamy et al. (2017)'s research found GNSS as the main means for navigation functioned reliably not only for navigation but also for communications and surveillance options (i.e., ADS-B). Cotton (2020) and Stouffer et al. (2020) explain that because GNSS is not as reliable in urban environments, a multiple-sensor fusion system with three or more sensors might be necessary for more advanced precision levels of navigation for UAM aircraft. Cotton (2020) argues that GNSS fused with electro-optical and infrared (EO/IR) sensors would improve precision during the departure, approach, and landing phases of flight. However, as operational volumes scale up, Low Area Augmentation System (LAAS) and WAAS are expected to provide even greater precision for navigation in low-level airspace. Stouffer et al. (2020) also recognized the difference in precision for different phases of flight and tested various combinations of sensors to find the most compatible pair suitable for the entirety of a flight. En-route phase requires less than 328 ft laterally and 125 ft vertically, approach phase requires ≈15 ft laterally and 5 ft vertically, and landing phase requires better than ≈ 5 ft laterally and ≈ 1 ft vertically. In the explored combinations, only three combinations were able to satisfy the requirements for all phases – GNSS+PNT, GNSS+LAAS, GNSS+WAAS. The next best option was GNSS+LEO, but it did not meet the requirements for the landing phase. In comparison with sUAS, UAM vehicles will not be able to use the same navigational technologies as the difference in reference points and operating altitudes cannot be matched between the two. Dual frequency receivers can boost GPS accuracy, which can enable real-time processing such as Ground Based Augmentation System (GBAS) or Instrument Landing System (ILS). Both will require GBAS, and ILS will require significant investment and maintenance for infrastructure at vertiports but could be used to provide corrections to aircraft around an airport to improve accuracy of the GPS position and ensure integrity of position data.

The level of navigational performance achievable by an aircraft and required for an airspace represents the final element defining navigational capabilities. From Prevot (2020)'s estimations of corridors in the vicinity of the DFW, RNP of 0.3 and 0.1 have the same hourly throughput, but RNP of 0.01 increases that throughput 14 times for a single altitude and four times for two altitudes. Comparing the capabilities of WAAS and Real-Time Kinematics (RTK), both options can achieve the RNP requirement of 0.01, maintaining their actual accuracy of approximately RNP 0.0004. Verma et al. (2020) presented similar technological capabilities for corridor simulations, where the flights had an RNP of 0.1. They had a comparable assumption to Prevot (2020), where the corridor dimensions will solely depend on the RNP capabilities of UAM aircraft. Bijjahalli et al. (2019) explored GNSS navigational capabilities and precision for unmanned operations in urban canyons. Like Prevot (2020), they found that RNP of 0.3 and 0.1 is too large for unmanned vehicles at low altitudes. Considering the nature and dimensions of the urban environment and its elements, they conducted a simulation to explore the appropriate accuracies for single- and dual-frequencies for standard and cost-augmented paths that might be applicable for UAM operations. The most accurate navigational precision occurred during a dual-frequency scenario with 10.5 ft accuracy 100% of the time and 6.5 ft accuracy 63.1% of the time. Kahne and Frolow (1996) state that GPS, provided by GNSS, is one of the most accurate tools of navigation services with an accuracy of 328 ft for many aviation users. Although, they also highlight that if a boost in precision is needed, LAAS or WAAS might be used to increase accuracy up to less than 3 ft.

Investigating the current and future trends related to the navigation aspect of UAM technologies, various solutions are expected to emerge in the near future. Volocopter (2021) identifies functions of navigation for initial UAM operations as GNSS, autoland capabilities, DAA functions, and contingency mitigation. As the number of aircraft increases and UTM/UTM-like networks grow, the navigational capabilities shall mature accordingly, enabling UAM to operate regardless of those systems. Thipphavong et al. (2018) expect a combination of current and newly emerging technologies to provide navigational service to UAM aircraft. While initial operations will be satisfied with GPS and other navigation aids, UAM operations will require more precision with the help of WAAS and supplementary "synthetic vision" technologies as the operational volumes grow. The need for greater accuracy is driven by meteorological conditions and urban environments with obstacles. Roche et al. (2018) argue that while unmanned aircraft would use GPS for navigational purposes, vehicle navigation performance will be crucial for corridor establishment and conflict resolution. It holds a considerable influence over the size of operational areas and the necessity for traffic deconfliction. Hence, advancements in navigational performance for unmanned aircraft may be required to satisfy safety standards. UAM aircraft can navigate using Performance Based Navigation (PBN) and Trajectory - based operations (TBO) to enable dynamic precision capabilities even in low visibility or visibility restricted conditions. It can also be combined with external data feeds and onboard capabilities (such as software, hardware and transmission mechanisms) to operate in greater route conformance and separate minima.

As helicopter operations are closely related to UAM, it is important to explore current RNP requirements set via Advisory Circular (AC) 90-105A for these operations. According to FAA (2016), RNP 0.3 provides a sufficient level of safety and performance for rotorcraft operations in en-route and terminal environments. Using this standard promotes non-segregated operations between fixed-wing and rotorcraft operations, smaller risk of icing in low-level urban environments, seamless transition between phases of flight, efficient routing, and safer approach procedures.

2.3.3 Surveillance

As UAM aircraft conduct flight operations at low altitudes and compact urban environments, surveillance has shown to be a crucial factor within CNS architecture. According to Hill (2020), UTM surveillance should be conducted by a set of ground, aircraft-borne, and satellite-based infrastructure. It would be mostly sustained by the PSUs, but precise monitoring might be enhanced by aircraft-to-aircraft or ground-to-aircraft surveillance technologies. Similarly, FAA (2020a) describes surveillance features where most of the data exchange happens within PSU networks shared with USSs, SDSPs, the FAA, and other stakeholders with access. Surveillance of UAM aircraft within corridors uses data sharing of operational intent, Remote ID, and supplemental information between those entities but without any ATC involvement. While UAM operations are not envisioned to use ADS-B Out or transponders during nominal operations in established corridors, during a proposed contingency scenario, UAM pilots are expected to turn on their transponder if departing its assigned corridor. From FAA (2021) UTM Pilot Program (UPP) testing, operational planning, and data-sharing among all participating users within the defined airspace were found to improve situational awareness about the operations in three different scenarios. Verma et al. (2020) mentioned that within operational scenarios where surveillance was based on submitted operational plans, routing, and use of ADS-B Out, the aircraft could establish a level of safety appropriate for such operations. Even though operators were simulated with different surveillance equipment in the scenarios, the average number of position messages per mile was relatively the same for both operators. Their conclusion indicated that higher operational volumes and frequent position messaging could stress the system, slowing two-way data flows and resulting in changes to areas of operations.

As a part of CNS architecture, surveillance depends on the on-board and airspace equipment and capabilities. Davies (2020) states that vehicle on-board capabilities depend on link performance, aircraft state, battery power, configuration setting, etc., to satisfy communication, Remote ID, conflict management, and other features under the surveillance hat. Airspace capabilities include airspace conformance, geo-fencing, ATC, flight planning, etc., to satisfy airspace authorizations and conformance, network load, constraints, and other monitoring features. CAAM (2020) envisions UAM monitoring in Canada to be conducted using a network of cooperative and non-cooperative surveillance using a mix of beacon and radar-based sensor systems, particularly in areas with high volumes of traffic. Onboard equipment would supplement the surveillance capabilities of the aircraft via weather sensors, GPS augmentation, and DAA systems.

Looking further into on-board surveillance options, Guan et al. (2020) compared different types of cooperative and non-cooperative surveillance. ADS-B has the highest detection range providing location, altitude, and speed, and being capable of tracking and communication. Traffic Collision Avoidance System (TCAS)/Airborne Collision Avoidance System – X (ACAS-X) has a high detection range providing distance and altitude, but its weight limits feasibility for UAS (potentially suitable for a larger UAM platform). EO, IR, and acoustic sensors have relatively short detection ranges providing relative bearing and elevation, but they are slow, susceptible to weather constraints, and are not usable in IMC conditions. Synthetic Aperture Radar has a decent detection rate providing distance and relative bearing, but it has low accuracy (and high size, weight, power, and computing requirements). Both Light Detection and Ranging (LiDAR) and vision-based systems have a short range of operations that might be affected by other factors. In addition, FAA (2020b) proposes the idea of using Remote IDs to achieve safety and security during UAS integration into NAS. Remote ID can be pre-installed on an aircraft to broadcast identification, location, altitude, velocity, etc. constantly, or added onto the aircraft to transmit the same information with a condition of line-of-sight. If a drone violates UAS regulations, FAA and other institutions can use the aircraft's Remote ID to locate its operator. Liu et al. (2021) explain that due to the nature of both environments and the design of unmanned operations, the Remote ID element will be a crucial part of UAS surveillance as it aids with issues like upload rate, range, accuracy, etc., that influence the quality and reliability of operation in an ATC controlled environment. Based on their research, the surveillance can be conducted via broadcasting to the nearest ATC station using ADS-B, radio frequency, and similar means, or via networks using cellular and satellite-based systems. They also compared different cooperative and non-cooperative means of surveillance, finding similar results to Guan et al. (2020). Lin et al. (2020) further explored the APRS for UAS surveillance within UTM. They found it to be one of the most suitable options for a lightweight, affordable, and reliable onboard system to relay data from the aircraft to the ground within the range of around 25 miles and at altitudes of up to 20,000 ft. Based on multiple tests, the surveillance system missed only one out of 1,331 packets of data, which is a 0.07% rate of missed information. The researchers found APRS to be dependable for UTM operations with an abundance of extra information that may be further used for vehicle analysis and maintenance.

Aircraft-to-aircraft surveillance has shown to be beneficial within the UAM environment. Hunter and Wei (2019) analyzed various types of surveillance such as radar, EO/IR sensors, dependent surveillance, and LTE/5G networks, focusing on challenges, such as implementation costs and LOS restrictions for radar, capacity limitations for ADS-B, etc. Their proposed concept of operations based on such challenges combines low-power ADS-B Out and 4G/LTE networks to ensure air-to-air surveillance with some integration of ground-based infrastructure. Similarly, Mueller et al. (2017) project that surveillance will be rather conducted using ADS-B within and outside the corridors using the aircraft-to-aircraft principle. ADS-B will be coupled with see-and-avoid techniques to achieve separation from other participating aircraft. Supplemental front-facing radar will be used for surveillance of aircraft ahead of them within the corridors. However, within UTM, UAM aircraft will rely on data sharing to provide a substantial level of surveillance.

In retrospect to on-board surveillance, off-board surveillance can be as beneficial within UTM. Lin and Shao (2020) looked at different surveillance options for flights at low altitudes under 400 ft and beyond that threshold. Using ADS-B like surveillance, the study examined two different data challenges for altitude above and below a specified altitude threshold. Their results showed 4G/LTE technology to be the fastest way to upload and exchange surveillance data within the UTM network with LoRa and Xbee taking second place with a two-second slower upload time. The pitfall of these technologies is that they are only available under 400 ft. However, using ADS-R for flights above 400 ft provides the best way to share ATC surveillance over 978 or 1090 MHz radios. In the review of various surveillance methods, Kahne and Frolow (1996) explain that satellite technologies coupled with GPS might be the solution to non-radar operations and ATC in remote areas. This combination allows reductions in separation minimums between participating aircraft.

In the comparison of different on-board and off-board surveillance capabilities, Thipphavong et al. (2018) emphasize that cooperative surveillance provides a much easier option as UAM can use ADS-B with a 978 MHz band to decongest 1090 MHz bands for other NAS-participating aircraft. Other concepts, like ADS-IP using IPv6 networks over a data link and Wide Area Multilateration using transponder broadcast for triangulation of positions were introduced as comparative means for accurate UAM surveillance. Alternatively, implementing non-cooperative surveillance has greater difficulty as it uses high-resolution cameras, IR detection, sensors, DAA technologies, or other means. Stouffer et al. (2020) reviewed ADS-B, ACAS-X/TCAS, dedicated short-range communications, Universal Access Transceiver 2, FLARM, LiDAR, frequency modulated continuous wave Radar, K Band, Acoustic Detection, RF Detection, and 5G. Based on the analysis of each system, for cooperative surveillance, the most reliable surveillance technologies are UAT2 and Mode C because they are compliant with ADS-B and provide the required level of accuracy, being highly usable for UAM. For the ground-based non-cooperative surveillance, none of the systems were shown to be feasible due to the nature of urban environments with many obstacles. For the air-based non-cooperative surveillance, a fusion of sensors was found to be feasible by UAM manufacturers; K Band, RF Detection, LiDAR, and IR sensing can be used for supplemental, short-range surveillance. Therefore, UAT2 was found to be the best option, which can also include rebroadcasting of position from sUAS to maintain separation within the UTM network. In any case, the final surveillance requirements for UAM will undoubtedly need a combination of all three different kinds to provide a considerable level of safety and assurance.

Within the current simulations and technologies applicable in the NAS of today, Hasan (2019) recognizes that the FAA does not have any eVTOL related rules or arrangements to ensure advanced level of surveillance (the most similar equipage is Mode C). Current positioning systems do not have the capability for tracking vehicles at low altitudes in urban areas, and they project a need for special beacons and dynamic routing to enable position monitoring above 400 ft. In the review of comparable UAM constraints, Vilar (2018) states that initially all UAM aircraft would be equipped with ADS-B as it will aid in establishing a CNS network with safe separation, procedures, and operations. On the other hand, they outline that because of UAM's dependence on ADS-B, any kind of cybersecurity attack or malfunction can present a lot of disruptions in operations by grounding the vehicles. Both Ramasamy et al. (2016a) and Ramasamy et al. (2016b) discussed the necessity of a combination of different cooperative and non-cooperative sensors to provide the required level of surveillance to participate with traffic within NAS. The proposed combination included active/passive forward looking sensors (FLS), acoustic sensors, ADS-B, and TCAS. In attempts to explore that idea, Ramasamy et al. (2017) correlated navigation and tracking errors of the host platform and tracked traffic correspondingly using various combinations of surveillance means to satisfy in-between vehicles and vehicle-to-ground data exchange. The results showed that the only combination that had any correlation was GNSS and ADS-B equipment. On the other hand, Cotton (2020) predicts that ADS-B, as one of the primary surveillance methods today, will get overcrowded if UAM use it for their operations, even at higher altitudes. They also explain that surveillance in urban environments requires either many receiving sites or high-power transmissions from UAM due to the nature of the environment and high RF reflectivity from the buildings resulting in multipath error. Since the research study does not consider the UTM concept but that the UAM will be non-segregated from air traffic, ADS-B with low-power TCAS might suffice in Class B airspace. As there are no requirements for cooperative surveillance in Class E and Class G airspaces, radar and sensor systems will suffice to uphold DAA techniques.

2.3.4 Separation of UAMs

To ensure UAM separation between other aircraft (UAM and other airspace users), CNS principles and technologies shall play a fundamental role in ensuring the safety in the sky. Hill et al. (2020) states that separation shall be ensured using PBN principles, sensors, and PSU network data sharing. Since the separation standards for UAM aircraft are much different from regular ATC procedures, factors like performance, operating environment, and flight planning will be crucial for ensuring safe separation. In addition, Guan et al. (2020) explains that each of those factors has a detrimental impact on the air traffic system. UAS separation will define the operational risk if too lax, risks increase and vice versa. In the analysis of studies that examined the separation minimums, they settled on 2,000 ft horizontally and 250 ft vertically for low altitude operations and 4,000 ft horizontally and 450 ft vertically for mid-to-high-altitude operations. Hunter and Wei (2019) focused on the issue of sUAS separation while enhancing airspace allocation. Even though they outlined various surveillance (e.g., radar, EO/IR, LTE/5G, etc.) and airspace propositions (e.g., alerting boundaries, strategic deconfliction, etc.) that aid in aircraft separation, an airspace concept was proposed to separate aircraft using traffic flows and rules of air adopted from current air traffic regulatory strategies. A combination of airspace structure and surveillance methods is expected to bring the recommended level of separation assurance within UTM networks.

Quite a few approaches have been presented in the literature regarding separation assurance. Ramasamy et al. (2016a), Ramasamy et al. (2016b), and Ramasamy et al. (2017) approached the separation assurance concept from a standpoint of developed CNS technologies aboard the aircraft. The NG-FMS installed by the UAM manufacturers would generate the appropriate resolution to potential path conflicts through data sharing and surveillance sensors via the UTM CNS concept. Being installed aboard and coupled with CNS equipment potentially reduces the response time and enables the additional automation of UAM vehicles to support a free flight concept of operations. Mueller et al. (2017) recognized that current separation standards would not apply to urban environments, comparing a standard 3-mile IFR separation radius to be as large as most of the San-Francisco area. IFR for ODM aircraft is much more challenging to implement compared to VFR with a "well-clear" separation. Three separation layers are expected to apply to ODM aircraft: a multi-layer strategy with specified corridors and alternating altitudes based on the direction of flight; separation assurance using time constraints; and collision avoidance used to make the appropriate maneuver when the aircraft are on the collision path. While the separation rules shall suffice for low-density traffic, V2V capabilities will help to preserve these standards as the operations scale up. For obstacle separation, a Minimum Obstacle Clearance Altitude (MOCA) will be satisfactory for low-density operations, but as the number of operations grows, sensors onboard the UAM vehicle will aid in remaining clear of the obstacles. The goal for the UAS separation service and by extension UAM services remains achieving operations with a rate of no more than one collision per 10 million flight hours, which is already a standard within the aviation community. While Cotton (2020) produced similar expectations for ODM, their analysis went further by identifying the approximate separation criteria for UAM interactions with different operations.

- Passenger UAM interaction with either a cargo UAS or a passenger UAM is proposed to maintain 250 ft vertical and longitudinal separation, while lateral separation will be defined based on the operating speed.
- Passenger UAM interaction with a VFR aircraft requires 4,000 ft lateral, 450 ft vertical, and ¼ mile longitudinal separation.
- Passenger UAM interaction with an IFR aircraft requires 3 miles lateral, 1,000 ft vertical, and 2 miles longitudinal separation.
- Passenger UAM interaction with an Autonomous Flight Rules (AFR) aircraft is proposed to maintain 500 ft vertical and ½ mile longitudinal separation and lateral separation based on the operating speed.

Liu et al. (2020) outlined two volume-based and one time-based separation techniques. The reachability-based approach predicts how far the UAS can reach and how long it would take considering its performance. However, it doesn't account for the performance of the conflicting aircraft, which provides insufficient time for a maneuver. The risk-based approach accounts for an acceptable level of safety, the performance of involved aircraft, and encounter dimensions, but it proved to be expensive due to the numerous calculations. The third approach, Tau, is based on the time differential between involved aircraft. While it is simple to use and it considers aircraft performance, it showed to be inconsistent with legal separation criteria.

Some surveyed approaches to aircraft separation have been tested and evaluated by researchers. Niklaß et al. (2020) propose to use the quadrocircular rule (similar to Mueller et al. 2017) for vertical separation of 165 ft by "flight level" for UAM aircraft. Eastbound flights would take odd altitudes in hundreds, northbound flights - odd hundreds plus 165 ft, westbound flights - even hundreds, and southbound flights - even hundreds plus 165 ft. A horizontal separation minimum of 2000 ft would provide up to 10 seconds for collision avoidance during a head-on scenario. During flight planning, the separation rules were applied and evaluated to assess the adherence to the requirements in operation using simulation. The study found that during the first scenario, only 4.9% of flights had a conflict, while during the second scenario, with twice as many flights, only 5.9% of flights had a conflict; finally, during the third scenario, with almost triple the flights of the first scenario, only 6% of flights were in conflict. Bosson and Lauderdale (2018) evaluated the impact of reduced separation standards for lateral spacing, temporal spacing, and arrival scheduling horizon using AutoSolver software. The baseline scenario included 0.3 NM horizontal and 100 ft vertical separation, 60 s sequencing specification, and 50 min arrival scheduling horizon. The three additional scenarios included reduced lateral separation from 0.3 NM to 0.1 NM, 60 s to 45 s sequencing, and 50 min to 8 min arrival scheduling horizon. Reductions in lateral separation resulted in lower conflict resolution numbers, from 100 to 74, with nearly all resolutions eliminated post-departure since the aircraft could fly closer to each other while still being appropriately separated. Reduction in sequencing showed a smaller decrease in conflict resolution numbers, from 100 to 83, with a rather significant decline in post-departure resolutions because the aircraft could follow on closer without a conflict. The reduction in arrival scheduling horizon decreased ground delay during pre-departure but caused a significant increase in the post-departure stage. Since the aircraft with flights longer than eight minutes did not pre-plan for their arrival vertiport, it resulted in the in-air delay on arrival while reducing the ground delay during pre-departure. Even though all three scenarios showed valuable results, a combination of these parameters might ensure reduced delay times both on the ground and in the air. Yang and Wei (2020) compared the authors' Monte Carlo-based algorithm (with airspace sectorization) and a free-flight scenario to examine the difference in possible separation conflicts. Using the base 0.5 NM horizontal separation, the algorithms used in the free-flight scenario resulted in a 90% chance loss of separation with five and more aircraft in the system and over 50% chance of near mid-air collision with six aircraft growing exponentially with each additional aircraft. The Monte Carlo research-based algorithm showed to be much more resilient in mitigating conflicts with a 1% chance of separation loss with 20 aircraft and almost no risk of near mid-air collision regardless of the number of aircraft.

2.3.5 Flight planning / PSUs

Flight planning addresses many factors responsible for ensuring safe operation across all types of aircraft including UAM. Lascara et al. (2019) looked at flight planning as an essential tool in determining the most favorable path for UAM flights. The authors envision the use of DDC and VFR corridors within various layers of airspace. As such, the route planning must consider aircraft performance, attain ATC and other permissions, and use only the most preferred pathways determined by the UAM fleet operator. Hill et al. (2020) envisions flight planning to be the responsibility of PSUs, as they have the most access to shared information and direct communications with ATM systems. A fleet operator would submit a proposed operations plan to the PSU with a flight path, planned arrival/departure times, alternate aerodromes, and other supplemental data, to which the PSU addresses strategic deconfliction and approval. PSUs provide modifications before or during the flight to be negotiated by the fleet operator prior to receiving the final approval.

Examining the different phases of the flight planning process, Davies and Patterson (2020) defined pre-flight, route adjustment, and collision avoidance. In the pre-flight phase, considerations involve pre-flight safety checklists, obstacle collision avoidance, weather information, planning for flights over people, GPS degradation, and radio frequency interferences. In the route adjustment phase, concerns include in-flight changes due to passenger emergency or vehicle system failure. They include terrain collision avoidance, sufficient aircraft performance, vehicle health monitoring, and in-flight safety precautions. For the collision avoidance phase, considerations should be given to non-cooperative aircraft, GA, or other traffic avoidance, as well as 4D route conflict resolution. Zhu and Wei (2019) focused only on pre-flight phase and proposed to use pre-departure trajectory planning as the primary tool for flight path optimization. Doing so would alleviate the pressure from DAA systems, re-route for weather and restricted areas, and minimize mid-air conflicts. Since each aircraft requires a dynamic buffer area for separation, trajectory planning software would predict and eliminate potential interactions that might arise. The researchers found that this algorithm promoted in-flight safety, aided in strategic decision-making while the aircraft is still on the ground, and increased flight predictability for other airspace users.

During flight planning, the mission profile must be accounted for and developed differently for UAM compared to other aviation users. Tuchen et al. (2020) found UAM-type travel within a multimodal traveling platform to be most beneficial for use cases in which a traveler has a sudden change of plans such that they need a faster way of getting from point to point across the city or other congested area. For this scenario, UAM flights provide support to the transportation network by relieving and avoiding ground congestion, as well as they serve as a separate mode of transportation planning tool for local and regional travel. According to Patterson et al. (2018), a typical UAM mission profile begins with aircraft taxi, where aircraft can either be manually moved or use wheels/hover for 15 seconds at 10% of cruise power. Next, the UAM aircraft would take off vertically at 100 ft/min for 50 ft. The aircraft would then transition into an ascending flight path; however, this operation varies by aircraft configuration. While helicopters can do this instantaneously, Vertical Take-Off and Landing (VTOL) aircraft can take additional time at this stage to transition the aircraft into its forward flight mode. Based on the planned altitude, the aircraft should climb from that position to the above-mentioned altitude at approximately 900 ft/min, meaning the aircraft would reach at least 500 ft one minute after take-off. Upon reaching the desired altitude, the aircraft enters cruise flight at the speed that maximizes its range with the capability of climb at 500 ft/min. The descending path will depend on the aircraft type before entering the 30-second hold over the landing area for additional clearances. A related requirement that was added to such execution is to have 20 minutes of cruise reserve. NASA (2020b) reviewed the best aerodrome approach path organizational practices for UAM approach procedures. The approach path includes similar fixes as the current approach plates – en-route fix, initial approach fix, intermediate approach fix, missed approach fix, and then vertiport.

Niklaß et al. (2020) highlight that UAM flight planning and scheduling processes have not yet been established. However, many ATM functions, such as trajectory planning, separation standards, airspace allocation, and flight rules, play a crucial role in that process. UAM flight planning process includes the following components: customer inquiry, registration, task flight plan, flight plan check, clearance, flight execution, flight control, and flight termination. In their simulation, the system’s Load Factor was calculated based on the minimal number of available UAM for each of the three expansion phases. Using the proposed flight planning technique, the results showed that a double increase for the second expansion phase and triple increase for the third expansion phase in the served number of routes, flights, and passengers decreases the average load factor. The flight path profile for the simulation was like Patterson et al. (2018). Although, in the real-world environment, the aircraft's performance and configuration will be a decision factors for flight profile setup. Bosson and Lauderdale (2018) discussed that because there is no one prevalent eVTOL aircraft proposed for use by fleet operators, it is much harder to establish a universal flight profile. While the flight phases are still the same for every UAM, transitions between take-off, climb, descend, and landing are still merely assumed. The reference aircraft capabilities taken for the simulation were from Cessna 172 with a climb rate up to 800 ft/min and airspeed of 170 kts.

2.4 Impact of UAM integration on air traffic controller workload

With the addition of the new entrants into NAS, it is crucial to evaluate the impact on ATC performance, as it is the most limiting factor for airspace capacity considerations. Kahne and Frolow (1996) explain that ATC workload is only a part of a bigger picture – airspace and resource capacity. While ideal sector capacity includes countless factors that stay perfect 100% of the time, the scope of ATC workload extends beyond human mental capacity and cannot stay perfect constantly. From a more UAM operations focused perspective, Thipphavong et al. (2018) established that UAM integration should neither burden the current ATC infrastructure and automation capabilities nor add any additional workload to controllers' routine beyond the current duties. UAM flights are initially envisioned to operate under ATC like VFR traffic, especially for flights within Class B, C, or D airspace. Constraints from ATC workload limits the upscaling the operations if improperly integrated. This implies that emerging operational concepts, technologies, and procedures that do not require thorough ATC interaction should enable high-density operations within the UAM paradigm. According to Rollo et al. (2017), increased ATC workload would only occur for airspace classes A-C, mostly due to the unreliable communication links incurring the transmission delay and poor connection quality.

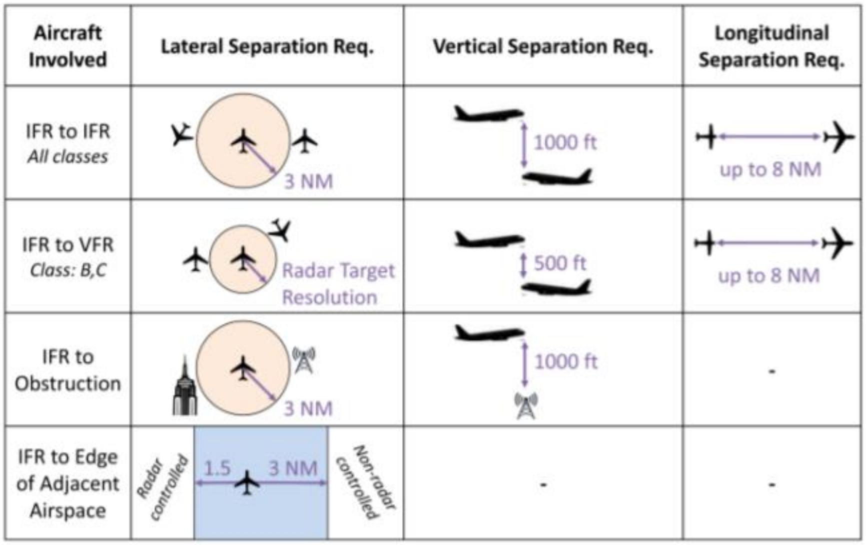
As the new operations emerge, controllers must assume a new set of responsibilities to accommodate the new entrants. Mueller et al. (2017) predicts ATC to have insight into ODM operations during nominal operations with the ability to intervene whenever safety may be compromised, which can eventually increase the controller's workload. As the system capacity and ATC workload are interdependent, certain approaches would need to be established to ensure the growth of operations without imposing extra work on the controllers. While FAA (2020a)'s authors do not envision much of the additional workload to be put on air traffic controllers, they outlined some of the new responsibilities that may challenge current ATM systems. As UAM aircraft are established within corridors, ATC does not control or communicate with those flights; though, they do have access to the operational data to ensure the safety of other NAS operations. Controllers do establish the corridor route availability as well as provide guidance to UAM aircraft that leave the corridor during a contingency scenario. Even though Goodrich and Theodore (2021) expect UAM operations to comply with the same regulations and requirements as the airspace operations of today, they expect most of the ATC-PIC communications to be handled digitally through the networks, along with PSUs and other users, to minimize the additional ATC workload.

Certain strategies have been reviewed to minimize the impact of UAM operations and mitigate the extra workload on ATC system. Nguyen (2020) analyzed multiple studies to find the impact of DDCs and other technologies on air traffic controller workload as the enabler of UAM airspace management within NAS. Upon completion, a combination of DDC and 4D RNP concepts was found to be the most effective mitigating resources against increased ATC workload from the emerging UAM operations. Vascik and Hansman (2017) dug deeper and estimated that over 92% of ODM flights would need to enter Class B, C, or D airspace. Doing so requires contact with ATC and would be detrimental to controllers' workload as the operations scale up. Since the structure of low-level airspaces around airports (i.e., upside-down cake) takes up a large chunk of airspace managed by ATC, it adds a lot to their workload, especially when coupled with separation assurance. This study focused on reducing the separation minima and allocating more operable airspaces for ODM operations scalability. VMC operations could relieve a lot of workload from controllers as pilots can self-separate via see-and-avoid and well-clear rules, which could support increasing the density of operations. Revisions of separation standards remain necessary to utilize the accuracy of modern CNS equipment and reduce operations densities in the environment. With respect to airspace allocation, improvements, such as airspace redesign to include only used volumes, definition of permanent Special Flight Rules Areas, and organization of dynamic airspaces with "open/closed" status (such as DDCs), would help to relieve some of the ATC workload and allow scalability of ODM operations. In the continuation of airspace allocation concepts, Vascik and Hansman (2020) proposed airspace volume “cutouts” that are procedurally separated from other traffic and independent from ATC service, yet they still adhere to minimum separation requirements. This concept could significantly reduce ATC workload by applying special flight rules and automated Flight Management System (FMS) technologies within those volumes. To relieve the workload during the initial integration, additional staffing would be sufficient to satisfy UAM demand; though, an increase in automation becomes necessary as the operations drastically upscale.

Some additional means to mitigate the initial UAM operations include coordination of activities with ATC or creation of new traffic regulating entities. CAAM (2020a) and CAAM (2020b) recognize that the current ATC system in Canada will not be able to support the growing numbers of UAM vehicles trying to operate within urban environments. Even though many of those aircraft are envisioned to be automated, such a system would still need supervision to ensure smooth operations. That’s why they recommend a new Remote Traffic Management-type facility to be established where controllers can manage more aircraft at the same time due to automation technologies and layered airspace. Vilar Llidó (2018) argues that if UAM operations show to be more of a burden on controllers and ATM system in general, it might not receive the needed regulatory support for full integration. They propose to initially integrate UAM aircraft within uncontrolled airspace to pave the way for legislation and non-segregated operations with other air traffic. To alleviate the present and increasing workload of controllers, which is a limiting factor on operations, AAM entities like PSUs or fleet operators should be responsible for the separation of UAM air traffic. Stansbury et al. (2019) examined the impact on airspace users when UAS encounter onboard equipment failures. Their results showed an increase in well-clear violations with other aircraft when failures result in the aircraft attempting a return to airport. They concluded that contingency planning must consider ATC stakeholders to mitigate the number of encounters between manned and UAS/UAM. Additionally, terminology within ATC policies and procedures can be obsolete for new entrants such as the terms “distress” and “urgency” which do not consider aircraft type when prioritizing off-nominal operational conditions.

In the assessment of ATC for UAM and UAS, Vascik et al. (2018a) identified ATC scalability as a leading constraint for UAM services. UAM and UAS services are predicted to overwhelm current ATC capabilities, and many government, academic, and industrial entities are working to meet this challenge. At the time of Vascik et al. (2018a)’s publication, the authors estimated ATC supports about 207,000 aircraft in the NAS, but expected the number of aircraft to increase significantly over the next three years with an increasing UAS presence from hobbyists and commercial UAS. Alongside the aircraft number increase, the short flights provided by UAM would increase daily flight numbers by orders of magnitude within smaller areas, leading to a higher airspace density. To meet these challenges, current rules for minimum flight separation would need to be drastically decreased and methods of communication must change, as shown in Figure 2. Without action, flight safety and short wait times would be impossible to guarantee. A transition to Trajectory Based Operations, such as the UAM Flight Corridor put forth in the FAA UAM CONOPs, where flight paths are agreed upon before the flight instead of in-flight, can be a solution (FAA, 2020a). This change will be supplemented by V2V communication using either existing Very High Frequency Digital Link transceivers or switching to a cell phone network-based system, as most urban areas already have ubiquitous coverage. VFR flights, such as those displayed at air shows, show a great potential in managing high density small aircraft operations.

Figure 2. U.S. ATC separation standards for IFR terminal area operations (Vascik et al., 2018a).



Aircraft Involved	Lateral Separation Req.	Vertical Separation Req.	Longitudinal Separation Req.
IFR to IFR *All classes*	3 NM	1000 ft	up to 8 NM
IFR to VFR *Class: B,C*	Radar Target Resolution	500 ft	up to 8 NM
IFR to Obstruction	3 NM	1000 ft	-
IFR to Edge of Adjacent Airspace	Radar controlled 1.5 3 NM Non-radar controlled	-	-

2.5 Infrastructure requirements necessary to support UAM integration into the NAS (including terminal environments)

In addition to the aircraft, procedures, and airspace planning necessary to support UAM operations, a substantial amount of infrastructure must be designed and implemented to enable UAM operations. These infrastructure types include UAM, UTM, and NAS general infrastructure, as well as vertiports and corridor requirements. This section additionally considers the impact of infrastructure and infrastructure design on public acceptance, which, in turn, influences UAM traffic density.

2.5.1 UTM + NAS general infrastructure

Infrastructure requirements will emerge to support UAM operations compatibility with UTM airspace and the NAS. For initial operations, Antcliff et al. (2021) suggested the use of smaller, secondary runways at major airports to support regional traffic as well as Conventional Take-Off and Landing (CTOL) and Short Take-Off and Landing (STOL) UAM aircraft. In addition, crossing runways may be utilized for Land-and-Hold-Short Operations (LAHSO). Secondary runway utilization would enable UAM operability, especially for those aircraft that are unable to use vertiports or existing infrastructure and services catered toward VTOL UAM aircraft. By using secondary runways, UAM aircraft can take off and land at large airports without majorly impacting conventional air traffic.

Several studies have also indicated what kind of infrastructure might be required for UAM operations. Stouffer et al. (2020) listed a few essential infrastructure features that included vehicle-to-vehicle communication, enhanced situational awareness tools, air-to-air and air-to-ground data exchange, and communication links. Some of the mentioned specifically required ground infrastructure included Mode-C multilateration, ACAS-X, 5G capabilities, advanced Doppler Ranger Gating Range, infrared sensing, bistatic radar, and acoustic detection. Some of the required infrastructure for ATM include ADS-B and integration of UAM aircraft operations into the FAA's

Data Comm program. These requirements are needed for expanded real-time communication, enhanced navigational accuracy, and assurance of proper separation and management of UAM aircraft within the PSU networks.

As UAM aircraft would be operating within segments of controlled airspace, especially near major airports close to large urban areas, some infrastructure requirements are expected to be set for such scenarios. According to the Air Traffic Control Association (2021), the infrastructure enhancements should be able to support the NAS as it continues to become more and more dynamic. State-of-the-art infrastructure integrating new, enabling technologies such as data analytics, 5G, Wi-Fi, machine learning, and precision tracking, would improve AAM safety, as well as enhance predictability, efficiency, and sustainability of this mode of transportation.

Wisk (2021) estimated that near-term eVTOL operations can be satisfied by leveraging already existing infrastructure in the forms of small- to midsize airports with established land-use, movement areas and ramps, ATC and airspace systems, and other commodities. This method allows to efficiently engage airports close to urban areas with low commercial air traffic. Nevertheless, additional considerations for existing small- to midsize airports lie within the necessary altercations in electrification and connection to the electric grid for eVTOL charging, TOLA location landside vs. airside for passenger accessibility, as well as the emergency response services for electric aircraft.

Hill et al. (2020), Air Traffic Control Association (2021), and Lineberger et al. (2021), all agree that supporting infrastructure development faces challenges due to limitations from energy generation, distribution, and storage used for UAM operations, such as vertiports, maintenance facilities, and other required infrastructure. Hill et al. (2020) and Lineberger et al. (2021) believe that further supporting infrastructure should include data collection and dissemination networks for UAM data exchanges, PSUs, UAM aerodromes (incl. corridors and UOEs), and fuel/power suppliers.

With the significant additional infrastructure needed to fully integrate UAM within the NAS, Thipphavong et al. (2018) expressed concerns over the amount of this infrastructure. Identified potential hazards relating to infrastructure included the lack of vertiport availability and inadequate ground crew training for maintaining safety margins. As vertiport availability is going to be extremely limited for initial segments of UAM implementation, especially when vertiports are occupied, damaged, or closed to traffic, it would be a pressing issue for safety insurance of aircraft within the NAS.

2.5.2 Corridors (Actual Corridors, Operating Areas, and Helicopter Routes)

Like the NAS's established network of routes and airways, numerous UAM routing concepts have been proposed leveraging a similar structure. Upon a thorough assessment, Prevot (2020) found that multiple tracks in corridors should be used for performance-based separation. Tracks going in the same direction should be separated 1,000 ft laterally, and tracks going in opposing directions being separated by 2,000 ft laterally. The study states that separation between aircraft within the track will be two miles in-trail. Adding onto that, Mueller et al. (2017) estimated a 164-ft lateral separation between aircraft. Both studies base the corridor structure on current VFR corridors, as it has proved to be efficient for VFR aircraft and provides a substantial level of safety for IFR and VFR traffic.

Regarding controlled airspace (especially near the airfields), Verma et al. (2020) provided a detailed assessment for UAM traffic integration. The results showed that routes would be pre-established by each provider. As these operators are conducting missions in the same airspace, all of them have access to the shared flight data and operational intent to increase situational awareness of all current and expected operations in the airspace. Each operator shall input their operational intent into respective scheduling software to ensure that their preferred routes are not in conflict via strategic planning between the PSU and ATC. It can also aid in case of planning for emergency contingencies. In case of a conflict, the scheduling service will identify a crossing point in routes and adjust scheduled departure times and estimated times of arrival to ensure the UAM aircraft in conflict have a proper separation minimum. In the case of a contingency or change of route in-flight, the requesting operator needs to submit an operational plan change request. Once approved, it is shared with the other operators via scheduling service. The contingency UAM aircraft would be deemed a priority, which provides a more direct routing with reduced delays to the new destination. The other operators are notified and re-routed. The study's recommendation is to use "UAM-authorized airspaces" within controlled airspace. These would be parts of the currently controlled airspace that have little-to-no traffic and may be given to UAM aircraft for either transit through the airport's airspace or landing and departure from on-site vertiport. This UAM airspace would be dynamic and based on air traffic flows, weather, airspace configurations, and other factors.

In FAA UAM CONOPs, the idea of UAM corridors was introduced as a method of conducting safe flights without ATC separation of the aircraft (FAA, 2020a). UAM Corridors are not meant to be a replacement for ATM or UTM, but a supporting method where flight separation along fixed paths controlled by a PSU. The corridors will initially be limited to point-to-point paths between aerodromes but are likely to evolve into more complex networks of connected aerodromes. They will have an internal structure as well as incoming and outgoing air traffic, operating at different altitudes in the airspace below Class A (18,000 ft and higher). Flight separation in the UAM corridors will be handled primarily by flight scheduling to de-conflict and raise awareness of new procedural rules. Ultimately, the UAM operators flying in the corridors are responsible for maintaining safety of flight and awareness of other flights happening in the area, but regulations governing operations in the flight corridor will have to be continually updated to account for increasing automation and BVLOS flights. ATC control of corridors will be kept to a minimum, with no two-way voice communication, ADS-B tracking, or clearances for flights within the corridor, other than setting corridor availability and handling the off-nominal events.

The FAA UAM CONOPs also introduced nominal and off-nominal UAM use cases (FAA, 2020a). The FAA considers nominal use of UAM to be flights conducted in the UAM corridors, which consist of planning, departure, enroute, arrival, and post-op phases. Two off-nominal use cases are given by the FAA. The first is a flight within the corridor non-compliant to the original flight plan. During the enroute phase, if the vehicle strays from the flight path for any reason, then the UAM operator should update their PSU and notify other PSUs of the event. Decisions will then have to be made as to whether the aircraft can re-enter the corridor and continue operations or if the operation should continue in the new airspace it occupies. Once a decision is made, the arrival and post-op phases will continue as a nominal case given there are no arrival interferences; an off-nominal report will need to be written. The second off-nominal case presented is the event of a failure resulting in a forced landing. In this case, the aircraft is expected to exit the UAM corridor with ADS-B transponder turned on and ATC notified, depending on airspace classification. The PIC of the aircraft should focus on flying, and the UAM operator should contact ATC with the contingency plan to mitigate risk to other aircraft. The PIC should find a suitable landing spot as soon as possible; an incident report should be written. To test the viability of so-called corridors, Nguyen (2020) organized a series of simulation scenarios to examine how these routes would work across different types of airspace. Within a planned scenario, the UAM aircraft takes off from a vertiport and climbs through a departure/arrival corridor, separating it from sUAS operating within UTM airspace. The aircraft continues to climb into Class G airspace and proceeds up to Class E airspace. Upon reaching Class E, the UAM operator chooses to enter the Class D airspace ahead or fly through a UAM VFR corridor. Once through the Class D airspace or VFR corridor, the aircraft follows a company-preferred route to enter a VFR corridor as the UAM aircraft approaches Class B airspace. The UAM operator chooses to either navigate around the Class B airspace or fly through multiple DDCs if it meets a higher navigation performance. The UAM aircraft would then begin descent as it exits Class B airspace into Class E and downward into Class G airspace until landing at the vertiport. This vertiport does not have a departure/arrival corridor; however, the separation between the aircraft and other UAM aircraft, as well as sUAS aircraft, is ensured through AVFR and UTM traffic information services. This study lacks the use of corridors within uncontrolled airspace, which is a notable difference compared to others. They are only being used within controlled airspace, including Class E.

Like Nguyen (2020), Lascara et al. (2020) explained how DDCs work within the NAS. DDCs will be a UAM-purpose infrastructure designed by stakeholders, such as local ATC, city planners, military, etc. They are expected to be dynamic as ATC would be responsible for setting each corridor's open-and-close status depending upon environmental conditions. DDCs within Class D, C, and B will be clearly defined to segregate traffic flows, and ATC shall treat DDCs like current VFR corridors. DDCs may also be defined in Class E airspace once the automated service is enabled. The study pointed out that UAM vehicles may be required to receive authorization from a traffic management service to enter or exit the DDC.

2.5.3 Public acceptance, noise impact, and safety

The placement and robustness of infrastructure impacts the public acceptance of UAM, which plays a significant role in its adoption, demand, and usage. Dietrich (2020a) states that UAM aircraft companies need to gain social acceptance to continue vehicle production. Achieving this goal might be particularly challenging since people are already resistant to helicopters, existing UAM vehicles, and other new technologies (also explored by Vascik and Hansman (2017)). The articles highlight noise pollution generated by rotors as an inhibiting factor in acceptance. Other factors include mistrust due to the system's novelty, underestimated advantages of UAM to the community, and the assimilation of UAM within society. UAM operations must increase accessibility and present its community benefits for the public to enhance appreciation for its services. Some advantages include faster emergency responses, connections between rural and urban areas, increased airport usage, and decreased ground traffic. In addition, UAM operations share similarity with other common public transport in such a way that there is no requirement to use security checks or customs, as within commercial aviation.

Many studies have highlighted the importance of localities and specifics of route networks within the urban areas in determination of public acceptance. Thipphavong et al. (2018) expect the demand for urban operations to remain in most metropolises, where it provides greater convenience than ground transportation. Although companies like BLADE helicopters are working to satisfy this demand, residents living around the helicopters' routes complain about the generated sound. Identifying UAM corridors for UAM operations will satisfy passenger demand and mitigate the impact of noise. Creating feasible routes between popular origin and destination UAM vertiports will also increase public acceptance. These UAM paths must avoid residential and business areas to reduce the produced noise. Routes must also avoid heavily populated regions as much as possible to prevent chances of fatal accidents. According to Wisk (2021), AAM operations would need to satisfy the public's auditory and visual needs. Similar to Thipphavong et al. (2018), the study proposed limiting hours of operations or route planning around minimally populated or already noisy areas (i.e., highways). Flight altitudes need to be evaluated to minimize the visual impact and increase visual acceptance. With pre-established AAM corridors, the flight paths should become more routine and less unsettling to the public. The study further explained that the AAM aircraft's auditory and visual factors would fade away when AAM aircraft benefit most of the community. Examples of community advantages include emergency response usage and affordable public transportation. The A36 Working Package #2's (Olivares, 2022) technical report contains a study of noise regulations and their applicability to UAM.

Another factor affecting public acceptance is the airport-community relationship. Wisk (2021) stated that "Once an airport falls out of favor with a community, it is exceptionally difficult to regain support." Besides noise complaints, privacy, emission, and other substantial effects may create additional tension in this relationship and remain unmitigated. An airport must maintain its surrounding community's trust to build, develop, and grow AAM infrastructure and presence.

Booz Allen Hamilton (2018a) identified various incentives for why their study's participants may support automation onboard aircraft. Many of the participants' support was conditional, meaning people would allow these vehicles' services if companies can satisfy most of the customers' preferences and requirements. Their results also showed responses from participants in Washington DC and Los Angeles are primarily supportive of UAM aircraft. Some of the determining factors were affordability and accessibility to the public, longer trips within the region, and the presence of human supervisors. The demand for UAM services is expected to increase if UAM companies satisfy these conditions. Booz Allen Hamilton (2018b) study found that environmental impacts and localities play a huge role in the public acceptance levels for UAM operations. Public acceptance is higher for electric UAM aircraft or operations in urban areas with higher background noise. The public is concerned about the vehicle's safety and would utilize UAM for long trips. On the other hand, factors like automation might be crucial for long-term public acceptance. Some of the other safety concerns include passenger behavior, pilot fatigue, and inappropriate aircraft control.

Studies showed that the characteristics of the UAM vehicles and the types of operations they are intended to perform influence the public perception of UAM safety and community health/lifestyle. Hill et al. (2020) found that demand for UAM systems would increase if UAM companies present successful safety tests. Their study also considered benefits to the community when UAM is introduced into the community lifestyle. Based on business case trials, UAM systems were expected to have a positive effect on local economies and lifestyles due to UAM being an additional public transportation option. UAM companies are also working to develop

UAM vehicles with lower carbon emissions and reduced noise pollution to satisfy environmental and community apprehensions. Similarly, CAAM (2020a) found that public acceptance affects the air traffic density, since it determines the number of UAM aircraft passengers would use. A separate survey found that some people would utilize cars more than public transportation due to the Covid-19 pandemic, which is a case of public health perception negatively impacting the initial demand for UAM aircraft. However, other respondents wanted UAM to encourage people to use public transportation systems more often than personal cars. If the efforts succeed, UAM aircraft demand is expected to increase. Fleet operators must convince the public about aircraft safety to encourage consumers to utilize their services. Additional test flights can be conducted over low-populated areas to reduce the chances of fatality or injury in case of an accident. The test flights can transition to more densely populated areas when these companies have made improvements and demonstrated safety from the earlier low-density trials. Consumers are expected to accept UAM operations when the trials prove successful in aircraft safety. On the other hand, UAM aircraft education should reach the broader community to increase public acceptance, including high schools, education systems, and indigenous communities.

Public acceptance has a tremendous impact on the locality of a UAM operations. The correct choice of cities where the implementation of UAM can be successful requires making an accurate demand analysis and prediction. One strategy for estimating the demand of this new sector is applying a qualitative approach, such as conducting surveys and focus groups to acquire a subjective opinion of future customers. Garrow et al. (2018) is one of the first works conducted on focus groups to estimate the demand for UAM. The study predicted that high-income users will be the first adopters of the air services due to busy schedules and ability to afford the services.

Quite a few studies have used intricate surveys to capture public perception of UAM from the US and other countries around the world. Chancey (2020) surveyed 240 participants from the US about their willingness to utilize UAM services based on the automation level and human pilot training and experience. The results showed that most respondents would use UAM services when a combination of automation and a human operator are present due to the participants' trust in the combination of both factors. The pilot's experience, however, barely has an impact on the public motivation in using UAM services since a human pilot's presence is more comforting than the pilot's experience. Kloss and Riedel (2021) surveyed about 4,800 participants in various countries, including the United States, to gain information about people's motivations and discouragements toward accepting UAM services. Based on the results, countries with dense ground traffic, frequent business trips, and low existing transportation systems wish to utilize UAM services in the future. Nevertheless, concerns about automated UAM aircraft's safety exist and people need proof of high levels of safety before permitting public use. Europe is expected to be one of the main leaders of the UAM market; countries such as Germany, UK, and France are highly invested in the R&D of innovative UAM system for commercial operation (taxis, package delivery, etc.). On May 19, 2021, the first EU study on UAM results were disclosed. The results showed that most respondents welcomed the UAM concept, but some of them still had concerns about some major aspects such as safety, noise, and environmental impact (EASA, 2021). One major part of the research was in the form of a survey completed by 4,000 citizens from six different European urban areas: Paris (France), Barcelona (Spain), Milan (Italy), Budapest (Hungary), Öresund (Sweden), and Hamburg (Germany). The survey showed that 83% of citizens expressed an initial positive attitude about UAM, with 64% and 49% willing to try drones and air-taxi respectively. According to the study, EASA is expecting that UAM will improve response times to emergencies by 71%, reduce traffic congestion by 51%, reduce emissions by 48%, and help to achieve a 41% development of remote areas. Like the studies of Kloss and Riedel (2021) and Yedavalli and Moodberry (2019), EASA's results highlight that younger people, higher-income groups, and families were found to likely support the UAM aircraft addition into transportation nodes. Most participants were reluctant to accept automated UAM services as pedestrians due to the perceived risk of the aircraft flying over them. Conversely, pedestrians, along with potential UAM service users, do support UAM aircraft strongly when there is a human pilot in control of the vehicle. Hasan (2019) surveyed over 2,500 people in the US on their acceptability of UAM technology. The results showed that 25% of responders are comfortable with UAM, while 25% claimed that they would not utilize the services even if the availability increases. This hesitancy was speculated to originate from five significant public concerns: safety, privacy, occupation preservation, environmental issues, and auditory and visual disturbances. Many consumers admitted being uncomfortable with autonomous technology since it's a new approach with a lack of safety information. As automation increases, some people also worry that this technological advancement would reduce job opportunities in multiple industries.

Even though the public of many countries are rather hesitant to accept AAM with open arms, others have a better outlook for this industry. Evaluating UAM public acceptance in Singapore, Lin Tan et al. (2021) found that many participants are comfortable with UAM operations providing public services. However, this acceptance varies with operating locations (i.e., people favoring UAM aircraft to work around industrial areas). While Singapore is one of the most accepting countries for UAM flights, the successful inception of AAM operations there may pave the road to the acceptance of other countries.

2.5.4 Multi-modal Transportation Considerations

This section addresses what factors influence passenger choice for selection of the UAM modality for their transportation needs. It also explores UAM network models, which are influenced by other transportation modalities, and simulation techniques that leverage the models.

Considering competitiveness of transportation modes, such as automobiles, public transportation and autonomous taxi service, Fu et al. (2019) attempted to understand the public's potential adoption of UAM service. Based on the market segmentation, several multinomial logic models were evaluated; safety, travel time, and travel cost were the most critical factors that would influence the public's choice. In comparison to the users of ground transportation modes, the UAM users are expected to stress the time variable the most (Fu et al., 2019). The results obtained in the study were integrated within the travel demand model, and applied to the Munich Metropolitan Region, resulting in UAM market share estimations ranging from 0.16% to 0.38% (Moeckel et al., 2020). Another study, Plötner et al. (2020), indicates that UAM travel for short distances (<5.4 NM) has a potential model share of 0.5%, by trying to employ UAM to complement public transport. Both studies concluded that the effect on existing traffic patterns from UAM is negligible. Wang and Ross (2019) concluded that most of the on-demand trips (taxis in this case) were transit-competing rather than transit-extending or transit-complementing. The findings of this study might also be applicable to UAM, as it has a similar functioning on-demand mode compared to taxis. Moekel et al. (2020) has conducted a study to identify demand and acceptance drivers for UAM by considering a meta-analysis of urban mode choice factor from 52 studies ranging from 1980 to 2017. Three different operational concepts of UAM were proposed by the author in accordance with various user segment needs, such as flexibility, comfort, and service cost.

Garrow et al. (2019) developed a survey with 100 questions, where they took into consideration factors such as lifestyle, personality, perception, attitude, and socio-demographic background. The survey was then used in Boddupalli (2019) to evaluate the preferences of 2500 people from five US cities and predict demand using a discrete choice model. It was found that cost and travel duration are the main decision-making factors. Literature from other modes of transport can also give insight into factors that may affect demand. For instance, Zhou (2012) and Nurden et al. (2007) found that age and economy are important factors for transport services demand. More specifically, Tyrinopoulos and Antoniou (2013) noticed that customers between the ages of 35 and 44 had a higher preference of using a private car. In terms of gender, according to Nurden et al. (2007), male participants were more likely to use public transportation. A few studies have investigated the inclination to pay potential of UAM users. According to the survey noted from Panel (2018), UAM users are even inclined to pay 2-2.5 times the original price of a taxi in the United States and Germany to reduce their travel time up to 50%. Rothfeld et al. (2021) conducted studies using MATSim application for the pre-existent scenarios: Munich Metropolitan Region, Ile-de-France, and San Francisco Bay Area. The application presented by Arellano (2020) for an impedance minimization location-allocation algorithm was used for the automated placements of UAM stations for a specified urban area. In the study, ground-based transport infrastructure is used for overflight instead of Euclidean flight paths, whereas larger infrastructure with high noise emission and traffic capacity is preferred for UAM overflight. It was concluded that the number of stations and distributions is essential for achieving the widespread UAM service coverage. UAM allows travel time savings of 3-13% compared to car trips under base case assumptions. While ground-based congestion does affect UAM travel times because of passenger accessing/egressing UAM stations, when compared to cars, UAM travel times are 51-82% less affected. It is estimated that UAM can provide 50-55 minutes in time savings beyond respective distances of a car ride.

Niklaß et al. (2020) conducted a study to develop a collaborative approach for the integrated method of design, modeling, and evaluation of UAM concepts. They developed a pool of low-fidelity analysis components and integrated it into a system of systems to quickly identify physical effects and cross disciplinary influences of UAM. Remote Component Environment (RCE) software made by Deutsches Zentrum für Luft- und Raumfahrt was used for analysis of capabilities related to various aspects of modeling, which included demand, trajectory, ground infrastructure, and cost, as well as air traffic flow and capacity management. Interaction between RCE components is based on the standardized data format Common Parametric Aircraft Configuration Schema. By adapting the already existing Common Parametric Aircraft Configuration Schemas, the efforts for implementing a feasible data format meeting the complex requirements of the developed modeling approach could be minimized. However, during the RCE workflow, the data exchange requires storage and retrieval time; a dynamic simulation of large traffic scenarios was challenging.

Wisk (2021) argued that many UAM services use eVTOL aircraft because of their minimal environmental and auditory impact. AAM transportation is projected to strengthen airport-community connections as this transportation mode ensures more direct access to the airport when passengers need to make a commercial airline flight. Passengers could also use eVTOLs to connect nearby vertiports and airports, such as tourist attractions and major hubs. Doing so shall relieve the congestion on the highways and within urban environments, as well as assist and potentially eliminate the need for outdated ground transportation services.

2.6 Coordination of non-segregated operations between the UAM and non-UAM air traffic

The coordination of segregated and non-segregated airspace elements between UAM and non-UAM air traffic must be addressed to ensure safe UAM integration into the NAS. National Academies of Sciences, Engineering, and Medicine (2020) explains that integrating UAM aircraft into the same airspace with traditional aircraft is more efficient than separating them. Even though the initial operations are divided between UTM and ATM, the long-term solution is expected to incorporate all operations in one conjoint system. Once UTM is fully established for UAS use, the UAM incorporation should be more straightforward. While current aviation procedures need alteration to meet UAM's operation requirements, Volocopter (2021) asserts that most UAM vehicles will be able to operate within the same airspaces alongside the traditional air traffic. Volocopter's UAM vehicle can adapt to any airspace class due to the necessity of successful airspace integration. Thipphavong et al. (2018) argued that UAM aircraft must create minimal alterations to the current aviation system when airspace integration occurs. The process of integration includes developing technologies, procedures, and resources to maintain UAM aircraft safety. UAM must cooperate with each other and other traffic to achieve safe airspace integration.

As many studies described using a corridor structure for UAM operations, our survey explores how the coordination of these structures and operations could happen. Nguyen (2020) recognized UAM integration into the current air traffic system would be challenging since the addition would expand the paradigm of traditional manned aircraft traffic. Despite UAM corridors being in place, pilots of this aircraft type must contact local ATC for operation permission if they're operating in the vicinity of non-UAM aircraft. The authors found a combination of DDC and 4D RNP systems could not only reduce traffic conflicts with non-UAM aircraft but also make ATC clearance unnecessary. FAA (2020a) explains that UAM aircraft might enter other airspaces whenever maintaining separation in the corridors becomes impossible, for example, due to weather. However, the operators must obey the airspace's rules while in the airspace outside of the corridor system. For example, the UAM pilot must activate ADS-B out and the transponder to communicate with ATC once they are outside the corridor in controlled airspace. After observing the helicopter's operations, Verma et al. (2020) found that digital communication wouldn't be possible for UAM aircraft with the current aviation system. The study proposed a UTM-like system that separates UAM aircraft from traditional aircraft, where verbal communication with ATC is unnecessary. With the use of designated airspace and route, segregation of operations would require constant deconfliction between UAM and traditional air traffic. Hill et al. (2020) envisioned UAM aircraft to operate separately from other air traffic in the UOE airspace. This airspace would be dynamic, changing availability depending on the nearest major airport's flow pattern updates. The UOE would be designed to exist alongside active-controlled airspace rather than separate with rules and regulations adopted based on the present scale of operations. Nevertheless, If UAM aircraft operate outside UOE, operators must obey that airspace's regulations. If non-UAM aircraft fly into UOE, operators must be able to participate in traffic management and separation within that environment.

If or when the non-segregated operations are achieved, specific separation methods shall be applied. While UAM are assumed to utilize UTM or UTM-like services, Mueller et al. (2020) envisioned UAM to be ultimately non-segregated from all other air traffic. They are expected to interact with VFR and IFR traffic in controlled airspace applying set separation standards. Nevertheless, various aircraft pairs utilize their separation procedures depending on the density of air traffic. Low density uses see-and-avoid and ADS-B for UAM and VFR traffic and segregation for IFR and sUAS. As per medium- and high-density traffic, they are not expected to be segregated but utilize DAA, UTM services, CNS, and V2V communications. Exploring possible UAM routing near busy commercial airports, Syed et al. (2017) found that UAM vehicles could fly around or below the traditional aircraft's approach area. This routing design allows UAM aircraft to be properly separated and avoid wake turbulence from the traditional aircraft while flying more direct paths.

The development and implementation of new flight rules must be considered in designing a non-segregated operational concept. Cotton (2020) acknowledged the need for different separation rules and standards for every flight type operating in the same environment, as there's a high chance of conflict between them. Integrating UAM into these regulations shall reduce the need for ATC communication to maintain separation and resolve those conflicts. The researchers evaluated a proposed concept of AFR for non-segregated operations in the same flight environment. The experiments were successful for mixed operations, even accounting for harsh IFR separation standards of 1,000 ft vertical and 3 miles in trail. Using automated prediction principles and tactical coordination, AFR flights can resolve conflicts within the non-segregated airspace without having to follow corridors or designated paths, which optimizes the use of available airspace and other resources. In the proposed concept of airspace cutouts, Vascik and Hansman (2020) evaluated the impact of airspace accessibility on AAM operations under different flight rules. The study found that if the AAM has access to VFR or IFR cutouts in various airport localities, it can give up to 75% more opportunities for efficient airspace use. The operations would be segregated based on the flight rules the aircraft adheres to. Using the DFR concept, Wing and Levitt (2020) stated that UAM and traditional aircraft could utilize the same airspace for the flights. As VFR and IFR co-exist in the same airspace, they found that DFR operations may be safely integrated into the same airspaces. Regardless, DFR aircraft must still give way to aircraft operating under different flight rules.

Exploring other constructs relative to operational segregations of air traffic, Guan et al. (2020) stressed that UAM should achieve a high level of situational awareness using collaborative and non-collaborative systems to reduce conflict with other aircraft operating in the same environment. They found such capability to be the most feasible option for enabling non-segregated operations. Considering factors like airspace segregation procedures, geofencing, third-party service providers, and ATC efficiency in managing UAM traffic, Vascik and Hansman (2017) proposed to segregate operations and airspaces based on the aircraft capabilities. Aircraft separation and airspace designations would prioritize UAS operations for lower altitudes and manned aircraft for 500 ft AGL and above. On the other hand, this approach might disagree with the standard first-come-first-serve method and would likely lead to system inefficiency. Lascara et al. (2019) identified that UAM systems are not impossible to safely integrate within NAS if they are based on existing procedural constructs, new decision-support tools, and clarity with the intent of the proposed regulations. Conformance with these methods is necessary to ensure safe and efficient

UAM integration into the NAS, minimizing the impact on other users. As per operational segregation, the concept of DDC would be essential to help to ensure sufficient separation between different types of air traffic.

2.7 Recent Industry Advances toward UAM Integration

UAM/AAM has emerged as a branch of air transportation that requires investigation of past, present, and future progress relevant to a successful establishment of the market. The team has analyzed the latest news from the UAM/AAM community to be inclusive of industry trends through news and other sources outside of traditional academically published routes. Bhadra (2021) shows that the latest FAA concerns and points of interest are extensions of battery density, improving autonomy, developing 5G/LEO communications and other physical infrastructure, regulations, security, etc. The near-term operations are expected to be piloted using certified eVTOLs in allocated airspace with possible waivers or exemptions.

With respect to air vehicle certification, Blain (2021) says that Joby Aviation has developed a partnership with US Air Force and the FAA to explore UAM as a new entrant, certification requirements, and other useful data about the commonality of such operations. As the first company to put eVTOL aircraft on the market and develop a prototype with over 1,000 flight hours, this partnership makes sense as a government opportunity to investigate the impact of UAM with Joby as its industry partner. Even though the partnership shall provide numerous insights on the operations and technology required to improve safety and agility of the new transportation type, certification remains the biggest concern as regulations concerning electric multi-rotor vehicles are not yet published. Nevertheless, current CFR Part 23 allows pre-liminary certification of the eVTOL, which can serve as an interim certification means until initial UAM markets have been established. Sampson (2021) also states that Alia eVTOL received airworthiness approval under the same program as Joby from the US Air Force. Alia's aircraft is currently in the testing stage to meet the proposed schedule of operational start in 2024. Collaborating with Air Force on eVTOL testing allows better allocation of needed technology and gaps in enabling the UAM operations.

As helicopter operations remain one of the most viable business transportation outlets, Cook (2021) argues that two of the upcoming bills imposing critical limitations to these flights in the New York City area could be detrimental to innovations and technological developments for similar operations. One of the bills is proposed to tighten noise regulations even more than current levels, while the other bill requires the collection of a wide variety of documentation relevant to each operation. The FAA already heavily regulates all helicopter operations nationwide, and, thus, imposing further limitations may affect up to 80% of current helicopter flight numbers.

Perry (2021) reported that while many companies, counting the emerging manufacturers, are trying to rush into eVTOL production and operations, Textron has remained hesitant to present its eVTOL design concepts. Their main concern lies in insufficient propulsion/battery technology – a major enabler of AAM. Based on past aviation trends of rushing into new design developments with improper propulsion, Textron shall avoid rushing to the market despite the risk of losing market demand to the early operators. In the overview of various eVTOL developments, Aerospace Testing International (2021) describes UAM generally as an extremely technology-driven market with the first flight happening by 2025. The article identified three designs: multicopter for short trips in urban areas (such as Volocopter's Volocity), lift-plus-cruise with two different propulsion types for lift-off and thrust, and vectored-thrust with propellers moving depending on the direction of flight. While fly-by-wire technology remains optional for commercial aircraft, many companies see it as a necessity for eVTOLs. Similar to Perry (2021), batteries were found to be one of the main concerns as they enable all the systems in the aircraft, including autonomous functions. Lilium has partnered with Lufthansa Aviation Training to ensure proper pilot training and aircraft testing. However, many of those progressions are very dependent on emerging regulations for eVTOLs. Poole (2021) sees the numerous investments in eVTOL technologies set too high of the expectations for the timeline of vehicles' roll-up. Lineberger et al. (2021)'s projections of first revenues by 2025 were deemed too optimistic due to unknown certification standards, demand, pricing, and airspace management tools. To add to that, Warwick (2021a) reports that Morgan Stanley's prediction was extended from 2030-2040 up to 2050 for substantial revenues.

To capture a larger market share, Volocopter is developing a VoloConnect to complete the set with VoloCity, Warwick (2021b) reports. They intend for VoloConnect to fill in the gap for regional travel and compete with Joby, Lilium, and Archer aircraft. While still in the works, Volocopter is expected to receive the necessary support from their stakeholders for this project and looking to transit from the prototype stage to fully operational service at the end 2022 or in the beginning of 2023 They are also proposing vertiport design named as Voloport currently in works in Singapore as part of the developing ecosystem basically used for testing ground which can also demonstrate support of AAM operations.According to Crumley (2021), the FAA has designed specific trials to evaluate the integration of sUAS with commercial air traffic in five cities nationwide: Atlantic City, NJ; Syracuse, NY; Columbus, OH; Huntsville, AL; and Seattle, WA. These locations were selected to represent a variety of environmental and operational conditions to ensure understanding of the scope and application of future practices. The main testable variables include flight intent sharing, notifications for flight activities, and FIMS/data sharing between USSs.

Polek (2021) says that multiple aviation stakeholders, such as American Airlines, Virgin Atlantic, and Avolon, have ordered 1,000 Vertical Aerospace aircraft for their regional connectivity. As aviation goes electric, most of these companies are trying to develop sustainable and emission-free networks of regional routes connecting their markets and hubs even further. In turn, that puts Vertical at breakeven by 2024 with the current prognosis. While the aircraft characteristics are still in the works, Honeywell and Solvay were contracted to supply avionics and fuselage parts.

To keep up with this serious demographic, congestion, and pollution rise, significant innovative actions and approaches must take place. According to Airbus, 60% of the world population is expected to be urban by 2030 (Airbus, n.d.). This congestion comes with an expected carbon emission monetary value of around $538 million in the US alone (Inrix, 2014). The new UAM business model can potentially satisfy this need and be a good alternative to the conventional ground transportation system by providing a safe, sustainable, and convenient solution. In 2019, the vertical flight society and NEXA Capital Partners, LLC advisors published a study which estimates that the UAM market represented by 74 cities worldwide would be worth around $318 billion between 2020 and 2040 with an ability to carry 1.3 billion passengers during those 20 years (Alcock, 2020).

This sector is being dynamically integrated within the Asian-Pacific region. Major cities in the region are expected to be the first adopters of UAM due to multiple investments from leading

Asian-Pacific companies aiding in the development of the UAM industry. Alcock (2020) states that by making an investment of $55 million in September 2019, Geely, the Chinese automobile group, shows serious intent in starting UAM operations in China. Hyundai and Toyota are also showing a considerable interest in the UAM sector integration. For instance, Hyundai made the all-electric S-A1 eVTOL aircraft, which can offer a range of 60 miles, maximum speed of 180 mph, and a cruising altitude between 1,000 and 2,000 ft. The aircraft can seat four passengers and takes 5 to 7 min to fully recharge. The aircraft will be finalized and manufactured by Hyundai, and Uber will provide the airspace support service and the customer interface. The two parties agreed to collaborate to build the infrastructure needed for this new concept, according to two reports from Hyundai (n.d.).

After the approval of the CAAC, the Chinese group EHang performed demonstration flights in Guangzhou, where it is headquartered, and some other cities around the country. EHang has previously done several demonstration flights in different countries such as Austria, Netherlands, and USA, specifically in North Carolina.

2.8 Vertiport Design and Planning

This section examines vertiports as essential elements of UAM infrastructure. First, the vertiport design and infrastructure considerations associated with those designs are addressed. Next, the literature review summarizes details related to the planning of vertiports as part of a multi-modal transportation network.

2.8.1 Vertiport Design and Infrastructure Considerations

VTOL aircraft, as a new form of air transportation, have been researched and developed in recent years. These new aircraft will use aerodromes known as vertiports. Published September 2022, the “FAA Engineering Brief No. 105, Vertiport Design” (FAA, 2022) provides interim guidance on the design requirements of facilities to support VTOL operations. Elements of vertiport design it addresses includes:

- Vertiport design and geometry,
- Marking, lighting, and visual aides,
- Charging and electric infrastructure, and
- Site safety requirements.

~~In 1991, the issuance of FAA AC 150/5390-3 provided guidance for vertiport design but in 2010 the AC was cancelled and the term vertiport appears in 14 CFR 57. Since then, the FAA has issued a draft of vertiport requirements and released Engineering Brief No. 105 (FAA, 2022), which contains draft guidance for vertiport design. Although still in development, the designs of these vertiports can be easily implemented and varies in levels of complexity, size, automation, and capabilities to enable high-density operations.~~ Many sources, such as the FAA, NASA, and private companies, such as Lilium, cover the design of these vertiports, showing many similarities, especially in design philosophy. As will be discussed later, this form of design implementation and overall agreement can give a universal application for these structures around the world.

As previously stated, many organizations have similar designs. Key differences are presented via vertiport contributions to the AAM community. According to NASA (2020c) and Lillium (n.d), the current design of vertiports accommodates various types of VTOL aircraft that can carry cargo and passengers. NASA has created three main concept designs of vertiports: vertihubs, vertiports, and vertistops. Vertihubs will hold non-utilized aircraft that may need maintenance, repair, and overhaul, as well as connect passengers to other modes of transportation. Vertiports will be used to connect passengers and cargo to vertihubs, vertistops, and services in high density locations. Compared to vertihubs, vertistops will be used to connect passengers to other forms of transportation but for a much smaller distance, such as connectivity to residential areas. These main design differences give vertiport developers the ability to apply different structural aspects at more varying and strenuous locations compared to traditional airports (NASA, 2020). According to Lilium (September 2020), the three key pieces to a vertiport are take-off areas, parking stands, and terminals. Lilium has also partnered with Dusseldorf and Cologne/ Bonn airports to establish regional air mobility as a new mode of transportation in the Northern area of Rhine – Westphalia region by 2025. According to Preis (2021), the runways consist of gates, taxiways, and pads for takeoff. An actual runway is unnecessary because vertiports are designed specifically for VTOL aircraft, which greatly reduces the utilized TOLA dimensions compared to traditional airports. Concept drawings from the FAA show these vertiports in unique locations depending on available space for pad installation (FAA, 1991). The concept drawings show vertiports built on top of buildings, rivers, and freeways, as well as within existing airports.

Lilium (2020) has provided many design concepts for vertiports with four sizes and three organizational designs. The four sizes are micro, small, medium, and standard. Micro consists of one TOLA with two parking spots, small consists of one TOLA and four parking spots, medium consists of one TOLA with six parking spots, and standard consists of two TOLAs and eight parking spots. The three organizational designs are linear, where parking spots are in a straight line and all aircraft take a similar path to the takeoff area; back-to-back, where parking spots are back-to-back with a similar path; and courtyard, where parking stands are facing each other in a square design with the TOLAs located at the end. Another design by Pries (2021) is a satellite style design, where the gates are in a semicircle, connected to a pad.

Pries (2021) also goes into more detail of current traditional regulations of takeoff areas. The study found that pads must be placed farther than 200 ft apart and operate independently. According to NASA (2020c), designers will need to consider what types of aircraft are used at each site and whether these aircraft would need runways or landing pads. The FAA designs consider runways and give a more in-depth look at both designs (FAA, 1991). Depending on the degree of approach, 6-degree or 9-degree, and the use of instruments or visual approaches, the area and distance of the TOLA varies. A presented example was a visual approach, where clearance is needed for a horizontal distance of 4,000 and 6,500 ft of width relative to the final approach and takeoff, or a pad and a transitional approach surface with a width of 200 ft on each side and a 250x250 ft pads. The planning section will go into further detail on clearance for these ports. From the design perspective, the number of gates or parking stands, length, and organization of the taxiways, as well as the number of pads needed, are all based on the number of aircraft using the vertiport and minimum separation distance. Depending on the vertiport, other modes of transportation services may be needed for passengers that have a substantial distance between vertiport and their destination.

Uber Elevate (2016) popularized a concept of vertiports in UAM networks, which aided several studies and analyses, including the concept of smaller and larger vertiports, also known as Limited Service Vertiports. A k-means clustering method was used as part of the study to optimize the selection of 25 out of 100 potential vertiport locations in London and Los Angeles by capturing the maximum number of long-distance Uber routes benefitting at least 40% with the use of the UAM network. An extension of k-means cluster has been made by Rajendran and Zack (2019) to an interactive algorithm to choose locations within New York City, so that the greatest possible number of taxi trips were within one mile of vertiport.

Even though the FAA currently does not recognize vertiports as TOLAs for UAM aircraft per se, many studies use this term predominantly for initial and final segments of UAM operations. Hill et al. (2020) defined the vertiport design's objectives to be able to handle extensive volumes of passengers and various aircraft types, obey "the safety and efficiency of the NAS," and be mindful of public complaints. Along with Sengupta et al. (n.d.), they explain the vitality of a vertiport's location; the limiting factors were flight areas, utility accessibility, current urban structures, UAM noise production, and environmental objects, such as trees, waterways, or prevailing wind patterns. Vertiport designs must also abide by adopted/required codes for public safety purposes. All vertiports need to satisfy FAA and industry-developed standards for all operation types. Many vertiports must also be able to handle UAM emergencies or alternative landings. Ginn (2019) recognized different levels of development for vertiports at UML-3 or UML-4, depending on the demand, services, and weather resilience. Regardless of its size and purpose, the vertiports must serve high-density traffic, recover from UAM incidents and emergencies, and remain resistant to configuration changes. According to Verma et al. (2020), UAM aircraft will use vertiports that can handle continuous UAM throughput and abide by existing guidelines. In the review of different vertiport experiments, the number of TOLAs in particular areas had a significant impact on air traffic and emergency handling. The industry must determine necessary vertiport quantities for safe and efficient UAM operations. Each vertiport was projected to handle one arrival and one departure per minute. Within one nautical mile, pre-set separation standards for the en-route environment would not be applicable in that area to ensure a higher and safer throughput.

Examining their design parameters, Sneth (2021) found vertiport design and intramodality with current transportation nodes to be the drivers for their future development. Vertiport design must consider the vertiport's location, spacing, environment, benefits to its area, and algorithm for operational zoning. These considerations affect the services vertiports provide to UAM aircraft and the public. Niklaß et al. (2020) argued that designers need to use 3D building information to determine the best takeoff and landing sites for UAM aircraft. The study described two vertiport designs: Level 0 as single points with no parking and Level 1 with multiple vertiports and parking capacities. While Level 0 might be a simpler approach to vertiport infrastructure, Level 1 structures represent either one TOLA with numerous parking spots in a circle around it or four TOLAs separated by parking areas in X-shape configuration. The vertiport design choice would depend on factors like downwash, wind patterns, urban topography, etc.

Quite a few researchers describe different operational scenarios and features that would be essential to consider when designing UAM operations. Hasan (2019) projected metropolitan vertiports to serve on average 20-minute trips. Vertiport operations would follow a hub-and-spoke method where hubs in urban areas connect the spokes in suburban areas. The hub entails vertiports on a cluster of rooftops to satisfy larger populations and connect multiple spokes with lower populations. Vertiports would provide limited on-demand routes to maintain current air traffic flow but may expand as UAM demand increases. In the beginning, vertiports must abide by the extant airport or heliport standards since there are no specific standards for vertiports at this time. The study projected around 2,500-3,500 vertiports distributed across metropolitan statistical areas to accommodate a range of 3-6 grounded aircraft at one time and quick battery swaps within the landing time. The accommodation numbers can change depending on the vertiport's location and conditions. In addition, Hall (2020) stated that turnaround times would determine the number of vertiports an area requires to satisfy UAM demand. Fewer vertiports will be necessary if turnaround times are quick. Addressing vertiport readiness, Bosson and Lauderdale (2018) considered the five-minute window before departure to be the standard time interval for industry-wide use. When creating a landing pad structure, vertiport design must reflect proposed vertiport scheduling standards and vertiport throughput characteristics to match passenger flights demand and vehicle maintenance intervals. To model the day-to-day operations, Guerreiro (2020) estimated that vertiports would follow the first-come-first-served algorithm. Since multiple UAM aircraft require a vertiport's services all at once, vertiport design was found to be critical. The study results showed that using the first-come-first-served concept might not allow vertiports to operate efficiently at all times, especially during peak times. They concluded that this concept of operations allows a throughput of over 80% of flights, which might be the most efficient for UAM operations and the safety of all other operating users.

A foundation of UAM operations with a well-designed ground infrastructure system is needed to reach the necessary demands of users and support the operation of eVTOL aircraft. Optimal locations for vertiport construction must be identified to establish such a system. Placement of vertiports should be considered as the most important factor addressing the physical constraints of nearby land use and the operational requirements of eVTOL aircraft. Antcliff et al. (2016) illustrated some ways to achieve these goals, using Silicon Valley as an example, by analyzing the features of existing infrastructure and aircraft operation regulations. Increase in vertiport availability and reduction in UAM first/last mile distance can be achieved by using different types of existing infrastructure such as vertiports proposed by Vascik and Hansman (2017). Potential vertiport locations are identified by considering the factor of demand distribution; k-means clustering algorithm is used by Lim and Hwang (2019) to identify potential locations of vertiports in Seoul, South Korea. Every identified cluster contained travel demands co-located with each other, and the centroid of clusters were regarded as reasonable locations for vertiports. A geographic information system-based approach was taken in Fadhil (2018) to place vertiports considering factors that influence the existing available infrastructure and commuting demand within the study area. Various weights were assigned to factors based on expert judgment, and location with different probabilities were selected as vertiports were identified. Optimized models might give more bits of knowledge to UAM network design in terms of giving ideal locations to vertiports and analyzing UAM functional characteristics. Daskilewicz et al. (2018) approached a method with an objective to minimize system travel time by proposing an Integer Programming (IP) model. However, the published paper doesn't provide any information regarding the formulation of the mathematical model; the authors were unable to identify optimal solutions. On the other hand, another model was proposed by Rath and Chow (2019) in New York City by applying the modelling structure of a traditional hub location for vertiport placements serving trips from downtown to three airports in the New York and New Jersey areas instead of cab services. Yet, there is a major setback due to poorly applied classical modelling structure without incorporation of UAM operational features. As with all aerodromes, vertiport location plays a huge role not only in accessibility to the customers and infrastructure but also in intramodality with other transportation nodes. Haan et al. (2021) found that vertiport locations in combination with ground infrastructure largely affect UAM transport demand, especially in the metro areas of New York, Los Angeles, and Washington, DC. Demand would also increase when vertiports are near central business districts or other places with the highest potential for UAM users. Upon Lineberger et al.'s (2021) analysis, the demand for AAM advancement suggested the FAA, the aviation industry, cities, and states start investing in vertiports to prepare for upcoming UAM transportation growth. Analysis showed a network of vertiports in one geographical area would be beneficial for the public, infrastructure development, and existing regulations. Vascik and Hansman (2017) established that placing vertiports in high-demand areas would increase UAM users' trip destination options. Analyzing currently existing heliports and helicopter services in Manhattan, they support this design proposal. While designers plan to have minimal vertiports in one area, businesses and investors seeing UAM's benefit will assist in vertiport growth. To increase vertiport accessibility, some of the landing requirements include tall landing gears, decreasing downwash, reduced noise impact, certification, etc. Infrastructure requirements include installing vertiports over highways, roads, rails, gas stations, superstores, other well-distributed businesses, over parking lots, on rooftops, or docks with floating barges. A vertiport's landing size depends on the UAM aircraft's average size, departure and arrival procedures, and average obstructions. For helicopters, the FAA AC 150/5390-2C suggests heliports have a minimum of two "inclined approach and departure paths separated by an angle of at least 135º."

From an analysis of the Greater Vancouver area, CAAM (2020b) identifies its need for twelve vertiports and one possible multiport within the metropolitan region, including airports and hospitals, to meet the demand of passenger operations. As UAM businesses evolve their aircraft from the initial fleets, suitable regulations will emerge for vertiports. AAM is projected to achieve street traffic reduction and air quality improvements using the proposed vertiport network. CAAM (2020a) says that designers will use existing heliports as guidance when creating vertiports to include battery charging stations for eVTOL aircraft and fuel stations for hybrid aircraft, perimeter security, shelters, and other items. The power grid also determines where a vertiport will be located as each requires electricity to function and enable UAM operations. Designers can salvage existing heliports and make necessary upgrades to serve eVTOL aircraft. As demand increases, multiports might emerge as a structure to accommodate growth. Multiports will handle numerous UAM aircraft and include restaurants, bathrooms, and shopping areas for passengers, similar to a traditional airport's design. In a TOLA network simulation, Vascik et al. (2018b) proved that multiple vertiports in one city are necessary for feasible UAM operations since most urban vertiports have only one landing pad. This vertiport system reduces air traffic with UAM aircraft since the vehicles have multiple landing options, especially in emergencies. Another finding limiting standard operations was the adjustment of flight plan and path for certain vertiports due to obstacles around its location. Altercations reasons include restricted access, extending flight paths, steep approach and departure angles. Like other studies, customer access, security, and TOLA's occupancy time were found to be other limiting factors for the feasibility of operations.

While regulations for vertiports do not yet exist, some studies have discussed expectations for these regulations. National Academies of Sciences, Engineering, and Medicine (2020) reports that the FAA is soliciting information about vertiport designs for development of new standards, regulations, and requirements of this UAM infrastructure. The current vertiport designs don't require large spaces since manufacturers of UAM aircraft are designing vehicles for small cargo or passenger transportation. Despite their minimal-space projection, vertiport designs are facing an issue of finding available locations in urban areas. While building vertiports in rural areas may be a quick solution, they would not meet the accessibility demands of the public, which decreases the demand for UAM transportation. Some propositions include "repurposing existing infrastructure" since it's both cheap and consumer accessible. Syed et al. (2017) designed potential vertiports using current FAA standards for heliports as guidance. Operational factors crucial to this type of landing area accessibility were its approach and departure paths, ground movement spaces, final approach, and landing area design, touch-down and lift-off area design, landing safety locations, etc., to promote landing efficiency and safe operations. Despite the vertiport's small operational area, current FAA standards for VTOL landing areas do not allocate establishments on highway interchanges due to varying heights affecting UAM operations. Many people will use UAM transportation when vertiports are at public-accessible locations, which increases aircraft commute and traffic. A solution would be building multiple vertiports and spreading them out in one urban area to reduce possible detours.

Another study was conducted by Willey and Salmon (2021) to formulate the vertiport selection problem for a UAM network as a single allocation p-hub median location problem. The problem lied in making modifications to choose the best vertiports and vertistops given any desired network construction required for scheduled transit flight. Vehicle speed and battery range were also taken into consideration as network dependencies. The value function was defined to maximize the reduction in travel time for passenger trips. Though monetary extensions, such as the total predicted revenue, would be more straightforward. The study results have established the dependence of network desirability on battery range, vehicle speed, and number of vertiports. Five different heuristic methods were used to obtain the optimal solution, including an elimination method that predicts which vertiports will be the most beneficial, Maximal Edge-Weighted Subgraph problem method, and three variants of a greedy algorithm, two of which use novel updating techniques to improve algorithm performance. Among these methods, the best performance is noticed by two greedy algorithms, which produced solution networks achieving on average 91% of the optimal value with computation times orders of magnitude lower than an optimal search.

Wu and Zhang (2021) examined the network design of eVTOL on-demand UAM service. Combining the modelling structure of the traditional hub-and-spoke problem and the mode choice modeling of individual travelers, a deterministic IP model was formulated. An additional constraint of spatial value of time distribution was proposed and pre-processed by analyzing the nature of the network design problem and the UAM trip characteristics to largely reduce the feasible region of the IP problem. The introduction of UAM service and non-uniform distribution of demand at different vertiports showed significant time savings. With the help of sensitivity analyses, it was observed that even though increasing the number of vertiports improves accessibility and UAM adoption rates, the case studies show that the marginal effect becomes insignificant when the number of vertiports exceeds 80. A combined analysis of these studies indicated that pricing imposes greater influence than any other factors from system performance to revenue generation. To summarize design, operational factors, and infrastructure, NASA (2020b) expects passenger vertiports to serve 80-120 aircraft operations per hour, allocating multiple large landing spots with a throughput of about 12 parked vehicles. High service vertiports will be around the urban centers' outer edges due to their size. Urban areas will also have vertistops handling one aircraft at a time, possibly for emergency landings. Medical vertiports will be available to reduce ground traffic affecting travel time for medical emergencies. This kind of vertiport facility must be widely accessible since medical emergencies can happen anywhere. Vertiports serving urban air freight will support 40-80 aircraft operations per hour. This type of vertiport would be mainly digital to reduce ATC's workload.

2.8.2 Planning Vertiports

Vertiports, when integrated and designed correctly, can be very effective modes of transportation. While the design of these vertiports is what makes them effective in operation with passengers and cargo, the size, scale, and tools at the disposal of a specific vertiport are crucial for efficiency. This is where planning comes into place, so that certain locations have the right equipment and space to repair and park VTOL aircraft and drones, along with maintaining passenger throughput and proper services for operations. Different buildings and services should be compared among all locations. Locations of vertiports differ by offered services and TOLA design (vertihubs, vertiports, and vertistops), according to NASA (2020). Vertihubs will be placed outside of suburban areas, vertiports will be placed in the middle of urban areas such as cities, and vertistops will be placed in suburban areas. With varying locations and unique services around the vertiports, it is easier to pick the locations based on the provided criteria. When all vertiports properly serve the major cities, they should be able to effectively run in unison. For example, vertihubs will be used mainly for storage and heavy maintenance of aircraft while offering transport to other vertiports and vertihubs, as well as supplemental services. Vertiports will transport people to and from urban areas, vertistops, and vertihubs. Vertistops will be placed in suburbs to make the travel between passengers' homes and major urban areas faster. Depending on location and regulations in certain areas, vertistops may need specific location requirements.

NASA (2020c) states that engineers will need to consider power and noise requirements while planning vertiport locations. Lim and Hwang (2019) considered placing vertiports based on population density to create better mobility for passengers, as well as allowing privately owned aircraft to use the vertiports. The study also considers creating maps of population centers to be used for most efficient vertiport placement in Seoul, South Korea. In terms of clearance for takeoff and landing at the vertiports, vertihubs and vertistops will generally be easy to clear due to the placement in suburban and almost rural areas. However, for vertistops in major urban areas, it may cause certain planning problems. If vertiports were to be put on tops of buildings, it would alleviate some problems, but the burden of approach paths would be the biggest hindrance in major cities. The FAA offered a solution, which included placing these ports on the tallest buildings in urban areas (FAA, 1991). However, building atop tall buildings is much easier said than done. These buildings would need to be a minimum of 4,000 ft horizontally to offer a proper and safe approach. NASA (2020) outlined that general demand requirements would need to be considered for vertiport placement. The number of gates will have to be chosen based on the arrivals per hour and occupation time before the next aircraft arrival (Lim and Hwang, 2019). Planners will have to consider offered services at each location, as well as where areas of the highest demand. According to NASA (2020), vertiports will have to follow strict regulations due to noise, ATC, other transportation, and quality assurance of the aircraft, as well as physical infrastructure. According to the FAA (1991), weather will also need to be taken into consideration, especially in regions that have heavy rain and snow. Some of these considerations include non-corrosive chemicals and pavement heating in the same areas as traditional airports. All these variables were found to affect planning. The closer vertiports get to implementation, the more variables planners will have to account for vertiport placements.

3 CONCLUSION

The research team surveyed over 130 articles with 105 cited in Section 4 of this report. Within this conclusion section, there is a summary of the key findings by research question. The team identifies research questions that must be addressed following the survey to meet the objectives of WP3 or serve as future work on later ASSURE projects.

3.1 List of Key Findings

This section summarizes the findings of the working package 3's literature and data review:

RQ0	What timelines for UAM/AAM capabilities as proposed by academia, industry, government, or other relevant stakeholders? (Section 2.1) • Technology and market drive the potential growth of UAM. • The surveyed literature show projections of first flight as early as 2023 at a UML-1 maturity under the NASA CONOPs UMLs, modest maturity at UML-4 by 2030, and greater maturity with increased automation projected by the mid-2040s or later. • Near-term air taxi services are projected to have demand only in major urban areas following infrastructure development.
RQ1	What are the minimum system, operational, and procedural requirements necessary to enable UAM integration? (Section 2.2) • UAM shall likely follow the innovations brought forth by UTM in its support of small, low-altitude UAS operations with non-FAA air traffic management enabling organizations known as Providers of Service for UAM, analogous to UTM's UAS Service Suppliers. • Organization of corridors and flight paths will depend on the development of supporting infrastructure, especially TOLAs. • The impact of UAM on the NAS capacity drives many considerations regarding what constraints must be set forth for UAM operations and modified for existing NAS users. • Airspace congestion in the urban environment or within the vicinity of airports is a key concern regarding NAS integration along with other challenges including weather restrictions, access to controlled airspace, autonomy linked with ATC, safety under congestion, airspace characteristics, and data flow between systems. • Surveyed literature proposed a range of altitudes for UAM, depending on the infrastructure used and advances in CNS technologies. The most commonly mentioned altitude range is ground/400 ft to 5,000 ft, based on the estimations. • The acceptance and use of automation for coordination between UAMs/PSUs and ATC is identified as a potential driver for reduced costs, safer operations, and

	enable greater UAM market growth; however, limitations such as the added weight, necessary aircraft equipage with supporting infrastructure, and the role of the human pilot on or in the loop of aircraft flight control. • 14 CFR Part 89 is presumed to be one of the main regulatory pieces for UTM and UAM establishment.
RQ2	What CNS requirements/best practices are necessary for UAM Integration? (Section 2.3) • UAM communications can include voice and data communication using common approaches discussed within literature including the use of PSUs, SDSPs, enhancements to C2 communication technologies, and UAM-to-UAM (vehicle to vehicle communication). • The FAA's FIMS network serves as a potential mechanism for UAM to NAS data exchange. • Initial UAM navigation shall be achieved via GNSS, DAA, and contingency mitigation function-enabling technologies. • UAM operations are expected to follow a pre-defined system of routes via corridors, which shall require advanced navigation system capabilities for UAM, such as the use of WAAS-enabled GPS to achieve performance-based operations. As UAM operations scale upward, adopting PBN will enable greater airspace density. • GNSS technologies must be sufficient to enable geofencing to safely maneuver UAM aircraft away from airspace boundaries along its corridor or designated air volume. • UAM surveillance shall be primarily a service of the PSU with potential augmentation via UAM-to-ground and UAM-to-UAM communications to achieve airspace situational awareness. • The PSU shall hold responsibility for surveillance of UAM with information disseminated to the FAA as required. UAM pilots shall be responsible for activating a transponder to notify ATC and other airspace users if deviating from its assigned corridor. • Airborne surveillance capabilities shall be limited by the operational limits and/or state of the UAM aircraft, including size, weight, power, configuration, and data link performance. • To ensure UAM-to-UAM separation within operational corridors, a combination of airspace structure and surveillance methods are needed. A layered strategy of mitigating air-to-air collision risk can be taken combining the use of corridors and alternating altitudes for flight, as well as time constraints and automated collision avoidance. • Within the literature, the flight planning is largely attributed as a function of the PSU with inputs from the UAM operator and/or fleet operator to negotiate changes.

	These engagements can be characterized as pre-flight, route adjustment, and collision avoidance phases. • Common UAM profiles include an aircraft taxi, take-off, ascending flight, cruise, descent, and landing with the characteristics of each phase dependent upon the aircraft's flight profiles and propulsion type.
RQ3	What is the impact of UAM integration on air traffic controller workload? (Section 2.4) • ATC workload can be considered part of airspace and resource capacity management, as UAM integration shall add additional workload on controllers and potentially inhibit the safety or capacity of the airspace. • ATC workload shall increase with the increase in UAM aircraft entering/traversing controlled airspace (i.e., Class B, C, or D), which requires those aircraft to contact ATC. • To reduce ATC workload, several concepts discussed in the literature delegate much of the nominal operations to the PSU with the ability for ATC to intervene whenever safety is compromised. • New UAM-related ATC responsibilities would include setting up corridor availability and managing off-nominal cases. • ATC scalability remains a significant constraint upon UAM with increased flight numbers within shorter distances, resulting in greater airspace density. • Communications congestion between ATC and UAM must be minimized to reduce controller workload. • Separation standards ought to be redesigned to permit reduced separation distances to enable more simultaneous operations.
RQ4	What are the infrastructural requirements necessary to support UAS integration into NAS (including terminal environments)? (Section 2.5) • Initially, major airports can leverage smaller, secondary runways to enable regional mobility, CTOL, and STOL UAM aircraft, which could mitigate the initial impact of UAM on conventional air traffic. • Essential infrastructure to enable UAM includes vehicle-to-vehicle communications, enhanced situation awareness tools, air-to-air and air-to-ground data exchange, and C2 links. • UAM corridors or similar concepts, such as UAM Operating Environments, were frequently discussed within the literature as a mechanism for managing airspace volumes for UAM flights. • UAM corridors can leverage lateral and vertical spacing to produce different airspace utilization cases, which were considered greatly and diversely within the surveyed literature. • Separation assurance can be achieved for UAM traffic through the use of airspace corridors, scheduling UAM traffic along corridors to eliminate collisions pre-flight, and pilot awareness to new procedures.

	• Off-nominal conditions considered within FAA's CONOPs include deviation from approved corridor/schedule. • Resource Management and Scheduling Services (RMSS) manage the scheduling of resources at a vertiport with SDSP serving as vertiport communication hubs for vertiport-to-vertiport and vertiport-to-UAM communication. • Time and cost represent major drivers for selection of UAM as a transportation modality. For instance, with short travel distance, ground-based taxis continue to compete with air-taxi type services. • The placement of vertiports within a UAM network is non-trivial, with practical considerations regarding site suitability, regulatory limits, and first/last mile distance for passengers. • Vertiport sites must consider the aircraft types to be accommodated and their specific takeoff and landing requirements.
RQ5	What strategies exist to coordinate non-segregated operations between the UAM and non-UAM air traffic? (Section 2.6) • Non-UAM/UAM separation presents some unique challenges, especially in high-density airspace environments. While corridors for UAM can enable their movement within shared airspace in predictable ways, research has also shown alternative methods, such as AFR, to coordinate non-segregated traffic that leverage automated, predictive conflict detection and tactical coordination for resolution.
RQ6	What are recent industry advancements toward UAM integration? (Section 2.7) • Literature has shown the top concerns from regulators for UAM include extending battery density, improvements upon automation, leveraging 5G/LEO communications, physical infrastructure requirements, UAM regulations, security, etc. • Multiple partnerships have been established between UAM manufacturers, government structures, and other community stakeholders to ensure establishment of proper testing, certification, and regulatory procedures. • Title 14 CFR Part 23 provides an interim means for certification of UAM until standards and guidance materials are developed. • Rising populations and transportation congestion within urban environments have led to worldwide efforts to consider the introduction of UAM into the transportation systems of major cities and regions. • Industry support has included recognized aviation industry leaders and new business entrants investing in R&D toward maturing UAM platforms, infrastructure, and adoption.
RQ7	What factors influence vertiport infrastructure design and planning? (Section 2.8) • Potential risks with early UAM include a lack of vertiport availability and inadequate ground crew training.

	• Regulations and guidance materials from the FAA and/or industry-based standard groups are necessary to guide vertiport development. • Primary limiting factors when selecting a vertiport site includes access to utilities, location of urban structures, UAM noise production, and prevailing environmental factors including natural obstacles, waterways, wind weather, etc. • The number of TOLAs and their location have a significant impact on UAM market growth as well as on air traffic and emergency handling, which can be unique to a particular metropolitan area. For example, a vertiport's proximity to airports can increase traffic density, and a vertiport's proximity to high demand services and activities increases demand. • The vertiport's design can be influenced by type (launch pads, runway-based, or both), vertiport size, spacing of launch pads, and configuration of the vertiport. • Vertiport design must consider what intersection transportation modes must be supported to enable passengers to reach their destination. • Considerations for planning vertiports including equipment / facilities needed on-site, charging requirements, aircraft storage needs, and anticipated passenger throughput. • Nearby services influence the type of vertiport appropriate for a site including vertihubs, vertiports, and vertistops. • While there can be greater demand for vertiports within the more densely populated areas of a metropolitan area, the complexity of these environments for operationally accommodating various UAM types and throughputs becomes limited (i.e., a vertistop in a city would face greater challenges than a vertiport in the suburbs).

3.2 Research Gaps and Next Steps

The research team identified the following research gaps from the literature review. These gaps include open questions posed by the UAM community and gaps identified by the A36 team.

- What are the operational constraints of UAM corridors?
- What are the operational constraints of UAM vertiports?
- What minimal CNS requirements are necessary to achieve non-segregated UAM operations?
- What are the roles and responsibilities of the PSU vs. ATC with respect to UAM flight planning, surveillance, information exchange, deconfliction, and contingency management?
- What data exchange must be supported by ATC with UAM stakeholders?
- What UAM system characteristics, infrastructure, and operational requirements influence ATC workload?
- What best practices can be established to guide vertiport design and planning?
- How can multi-modal transportation network simulation enable future UAM research?

The research team shall consider these research gaps when preparing the research task plan for WP3. Questions outside of the scope of the project will be captured as proposed future work to be conducted by the ASSURE FAA Center of Excellence for UAS.

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