Evaluation of Initial and Mid-Term Air Traffic Procedures for Urban Air Mobility Operations

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Urban air mobility (UAM) operations are expected to expand in scale over the next several years as novel aircraft types, including electric vertical takeoff and landing aircraft, are certified and begin operations. These new aircraft may increase safety, decrease noise, and lower operating costs compared with helicopters, allowing them to operate in ways existing aircraft do not. It is vital that these expanded operations are compatible with and do not disrupt existing operations or the air traffic management system. To study the ways in which scaled UAM operations can best integrate in the national airspace system, NASA and Joby Aviation partnered to conduct a high-fidelity air traffic controller-in-the-loop study. Building on air traffic procedures used to manage high tempo operations in other parts of the airspace, new procedures, routes, and communications protocols were developed and tested by retired controllers in NASA's Future Flight Central tower simulation facility. In addition, new cooperative airspace constructs in the form of corridors were developed to understand their potential contributions to even greater scales of operation. The controllers managed traffic scenarios in the Dallas-Fort Worth and Dallas Love Field airports consisting of fleets of up to 100 UAM aircraft operating alongside traditional traffic. Metrics for air traffic controller workload, duration of communications, departure delays, and other measures of allowable aircraft throughput were collected. The analysis indicates that using today's procedures for initial UAM operations under nominal conditions could enable up to 40 operations per hour to an airport's central terminal area if that involved crossing a runway and up to 55 operations per hour if reaching the central terminal did not involve crossing a runway. Operations at these tempos did not delay or otherwise interfere with simulated runway traffic and were rated acceptable by the air traffic controllers. The new corridor constructs dramatically lowered controller workload in certain circumstances, suggesting they may be effective in further increasing the allowable scale of operations.

I. Nomenclature

AAM	= Advanced Air Mobility
ADS-B	= Automatic Dependent Surveillance Broadcast
ATC	= Air Traffic Control/Controller
ATIS	= Automatic Terminal Information System
CBA	= Class Bravo Airspace
DAL	= Dallas Love Airport
DAL Local	= Air traffic control position within the Dallas Love Field Tower to manage primary runways
DAL Helo	= Air traffic control position within the Dallas Love Field Tower to manage helicopters and UAM traffic
DFW	= Dallas Fort-Worth Airport

eVTOL	= electric Vertical Takeoff and Landing
FAA	= Federal Aviation Administration
GA	= General Aviation
HITL	= Human-in-the-Loop
IFR	= Instrument Flight Rules
LOA	= Letter of Agreement
NAS	= National Airspace System
NASA	= National Aeronautics and Space Administration
PIC	= Pilot in Command
RNAV	= Area Navigation
SME	= Subject Matter Expert
STARS	= Standard Terminal Automation Replacement System
UAM	= Urban Air Mobility
VFR	= Visual Flight Rules
VMC	= Visual Meteorological Condition
WAK	= Workload Assessment Keypad

II. Introduction

The Urban Air Mobility (UAM) concept is part of Advanced Air Mobility (AAM), a joint initiative between the Federal Aviation Administration (FAA), NASA, and industry to develop an air transportation system that uses new electric (i.e., green) air vehicles in geographical areas previously underserved by traditional aviation. Market forecast studies predict that there will be demand for alternative modes of air transportation using electric vertical take-off and landing (eVTOL) aircraft. UAM expands transportation networks by introducing short flights to move people and goods around metropolitan areas [1,2]. UAM is expected to improve mobility for the public, alleviate road traffic, reduce trip time, and decrease strain on existing public transportation networks. However, various challenges exist to make the introduction of UAM operations successful in the U.S. National Airspace System (NAS). These include, but are not limited to, integration with existing airports and airspace, provision of air traffic services (e.g., separation), vehicle design and certification, infrastructure development, and community acceptance [3].

UAM will operate within a regulatory, operational, and technical environment that is incorporated into the NAS. In the UAM Concept of Operations (ConOps) [1], the FAA retains regulatory authority and is responsible for establishing operational parameters and maintaining oversight. The FAA's UAM ConOps describes flights at low altitudes (i.e. below 5,000 ft AGL) with minimal disruption to established conventional aircraft traffic and limited voice interactions with air traffic control (ATC). Early stages of UAM will likely use existing procedures to safely integrate UAM with conventional flights. This would involve flying under 14 CFR Part 135. This initial UAM ecosystem will utilize the current infrastructure such as routes, helipads, and ATC services, where practicable.

The FAA ConOps also defines Mid-Term operations that may have higher tempo, new airspace structures, and third-party automation. However, instead of FAA automation systems and ATC managing the flow of traffic, FAA's UAM concepts envision a third-party service provider would perform this role as the Provider of Services for UAM (PSU) network [2] in collaboration with the pilot and fleet operator.

One proposed operating innovation that can help with the scalability of UAM is establishing corridors [1]. The FAA's UAM ConOps posits that new airspace structures such as UAM corridors include the following design criteria: 1) minimal impact on existing NAS operations, 2) no or minimal additional ATC services, 3) public interest considerations such as noise, safety, and security, and 4) customer needs. The new airspace structures would need to be designed around large airports and urban areas where the initial market demand is predicted to exist. Still, the airspace available in urban environments is limited by the height of buildings, the impact of weather (e.g., wind gusts), community privacy needs, and a clearance envelope.

To investigate the potential of the airspace to accommodate UAM operations, in 2018 NASA conducted research comparing the use of existing helicopter routes in Dallas-Fort Worth (DFW) airspace for initial UAM operations to a modified set of procedures define in a Letter of Agreement (LOA). These new LOA procedures dictated named routes that pilots could request, streamlined communications to request Class Bravo entry clearances, and other pilot and air traffic controller responsibilities. The new procedures allowed higher aircraft throughput than was possible with today's procedures and reduced communication workload by twenty percent [4,5,6,7].

This paper describes a follow on, joint human-in-the loop (HITL) simulation effort by NASA and Joby Aviation that builds on the results of these previous simulations. It extends that work by comparing the LOA condition for initial UAM operations to mid-term operations that includes corridor airspace structures and some other changes to the operating environment. This is the first reported air traffic controller-in-the-loop evaluation of the corridor condition in a high-fidelity simulation environment. The following sections will describe the routes, scenarios, and operating conditions along with metrics used to evaluate feasibility from the air traffic controllers' perspectives. The results section presents the traffic levels that were feasible in each condition and concludes with recommendations for extending the scope and applicability of evaluations like this one in the future.

III. Approach

In preparation for conducting a human-in-the-loop simulation, multiple preceding efforts were conducted with subject matter experts (SMEs) to develop and enhance potential airspace procedures and information requirements. These preceding efforts included two tabletop exercises and a shakedown activity. The first tabletop exercise was conducted in-person over a span of two full days in May 2023 at NASA Ames Research Center and explored notional airspace routes/corridors and associated procedures, information exchange requirements between ATC and the UAM on-board pilot-in-command (PIC), and other operational details use cases. Four SMEs, all of whom were retired air traffic controllers from the Dallas-Fort Worth (DFW) metropolitan area, participated in the tabletop exercise. During the exercise, SMEs were presented with a set of use cases and routes in the Dallas area that were jointly developed by NASA researchers and Joby Aviation. The second table-top exercise was held in June 2023, it invited SMEs from DFW metropolitan areas, industry partners, government, FAA and National Air Traffic Controllers Association (NATCA). The findings from the two tabletop exercises and successive efforts were used in preparation for the HITL simulation. A shakedown simulation was conducted in August 2023 where the procedures were evaluated with retired controllers who managed the traffic and provided feedback to researchers. Feedback included suggestions to improve the procedures, displays, and information needed to manage both UAM and conventional traffic. The shakedown simulation was also used to establish appropriate traffic levels in the scenarios.

A. Experimental Design

The experimental design was a 2 X 2 with the independent variables of UAM traffic density (i.e., low versus high) and airspace procedures (i.e., Initial versus Mid-Term operations) as shown in Table 1.

Table 1. Experimental design.

	Initial	Mid-Term
Low UAM Traffic Density	Condition A	Condition C
High UAM Traffic Density	Condition B	Condition D

There was a total of 16 counterbalanced runs of 45 minutes duration with four runs for each condition. The runs were blocked by airspace procedures condition, with the Initial operations runs being completed first followed by Mid-Term operation runs. Runs included time for questionnaire completion and a 15-minute break. The assumptions pertinent to the conditions are delineated as follows:

1. Initial Operational Condition Assumptions

The Initial operations condition assumed that takeoff and landing locations will be available for public use and the aircraft will utilize certified eVTOLs operating under Visual Flight Rules (VFR) in Visual Meteorological Conditions (VMC). Vertipads located on DFW and Dallas Love field (DAL) airports were located in non-movement areas. Current day airspace structures and automation such as Standard Terminal Automation Replacement System (STARS) [8] were assumed. ATC would be required to radar identify and clear each UAM aircraft into or out of the Class B airspace via the coded routes. ATC also retained the right to deny or delay entry into or out of the Class B airspace via the coded routes, if they deemed it necessary.

A PIC, who is familiar with the LOA designed for these operations in the DFW and DAL areas, will be on-board these aircraft. The LOA will reduce communications by:

- Pre-assigning beacon codes to the aircraft (PIC would squawk their pre-assigned beacon code prior to contacting ATC).
- Coded routes (which include specific altitudes and airspeeds for each waypoint) inside Class Bravo and Delta airspace.
- Defined arrival and departure procedures.
- Ensure the PIC has the current Automatic Terminal Information System (ATIS) without the need to state it.
- Eliminate arrival/departure advisory, i.e. landing will be at your own risk.
- Eliminate the need for ATC to verbally cancel radar services as an aircraft exits the Class B, this is done via predefined exit waypoints.

2. Mid-Term Condition Assumptions

As the tempo for UAM operations increase, a change to the rules and regulations is expected. These changes may include a waiver of the Class B separation criteria between VFR aircraft and to VFR/IFR aircraft that weigh greater than 19,000 lbs and all turbojets (FAR 7110.65 Chapter 7-9-4(b)). This will impact separation of UAM aircraft inside the corridors with aircraft (19,000 lbs. or greater) and all turbojets outside the corridors. They will only be planned inside Class B, C, and D so that flexibility that exists in Class G and E can remain intact. ATC reserves the right to utilize corridor airspace at their discretion with non-UAM aircraft. LOA will still exist providing further reductions in ATC/PIC interactions such as:

- No clearance required to enter the corridor.
- No requirement to radar identify the aircraft using the corridors.
- UAM operators must meet performance and operating requirements.
- ATC will not provide separation services, traffic advisories or safety alerts to UAM aircraft within the corridor.
- PIC will Squawk 1207 prior to entering a corridor.
- PIC must monitor appropriate ATC frequency for the airspace the corridor is in.
- PIC must adhere to all waypoint altitude and airspeed restrictions.
- Defined arrival and departure procedures.
- Eliminate arrival/departure advisory, i.e. landing will be at your own risk.

A capability currently exists in STARS that provides controllers with a “quick-look” function that allows ATC to access callsigns for the UAM aircraft within the corridor, when required. This capability is enabled through Automatic dependent Surveillance – Broadcast (ADS-B) messages that allow automatic correlation of aircraft callsigns. Two-way radio communication will not be expected during nominal operations inside corridors. For these operations, automation will assist with demand capacity balancing, strategic deconfliction, spacing and sequencing. See and avoid will also be employed by the pilot for any maneuvers.

B. Participants

Four retired air traffic controllers from DFW and DAL Towers were recruited as participants, who had not participated in the tabletop or shakedown exercises. The participants worked traffic in NASA’s Future Flight Central (Figure 1), a fully immersive 360° virtual air traffic control tower. Data were collected from two controllers in each tower, one local controller and one helicopter (Helo) controller. The participants rotated through these positions. Eleven pseudo-pilots managed the UAM and background aircraft. Participants provided subjective measures of workload and performance during and after the simulation, and objective measures were collected during the simulation.

Figure1. Future Flight Central at NASA Ames Research Center

C. Test airspace

The primary focus was the Dallas Forth-Worth Class Bravo Airspace (DFW CBA). The DFW CBA is approximately 370 square miles and encompasses two major airports, DFW and DAL. The CBA is divided between the two control towers and controllers in each tower are delegated responsibility for providing air traffic services to aircraft within their respective airspaces. VFR aircraft must receive an ATC clearance to enter and operate within the CBA. In exchange, aircraft operating in the CBA are afforded ATC separation services appropriate for the size, type, and flight rules of aircraft they are flying and those they are being separated from.

Although not the primary focus, operations in Class Echo (Class E) and Class Golf (Class G) airspace were also used in this research. Class Echo airspace is controlled airspace and may begin at ground level, 700 ft or 1200 ft above the ground depending on the location. Within the study's research area, Class E airspace starts at 700 ft above ground. While ATC controls and provides separation services to IFR and some VFR aircraft, VFR piloted aircraft are not required to contact ATC to operate within Class E airspace or receive services. Additionally, VFR pilots must adhere to strict cloud clearance and visibility requirements while in Class E.

1. Vertiport Locations

Table 2 and Figure 3 show the nine vertiport locations that were used to create a network for UAM routes and corridors. Four vertiports were selected within the uncontrolled Class G airspace, all of them being existing heliports, while the rest of the vertiports were located in the Class Bravo. The only existing heliport in Class Bravo is 49T, marked as DF-49, in the Dallas Downtown area. A list of the vertiports is provided in Table 2 along with their simulation reference codes (e.g. DF120) and whether they are existing locations.

Table 2 List of vertiport locations inside and outside Class Bravo used for the study

Vertiports inside Class Bravo	**Vertiports outside Class Bravo**
DFW Terminal E Parking Garage: DF120	Frisco Superdrome (existing): DF99
Periphery of DFW: DF7	Denton (existing): DF50
Business Ramp at DAL (existing): DF60	AT&T Stadium (existing) (DF00)
DAL Parking Garage: DF61	Garland (existing) (DF70)
Dallas Downtown T49 (existing): DF49	

2. Design of Corridors

The simulation utilized routes and cooperative airspace structures, or corridors, in and around the Dallas Fort Worth Metroplex Class B airspace. Airspace for UAM operations was identified for Class Bravo and Class Delta airspace, no such airspace was identified for Class Echo or Golf to keep the airspace's current flexibility intact. Because traditional air traffic occupies higher altitudes (primarily above 1700 ft AGL), airspace for UAM operations was identified to take advantage of altitudes under 1700 ft to minimize the need for deconfliction and minimize ATC workload. A multi-step process utilized wake advisory criteria (2500 ft lateral separation or 1000 ft vertical separation), published Instrument Approach Procedures (IAP), Standard Instrument Departures (SID), and historical flight data to identify the usable airspace for which UAM can fly with little ATC interaction [9]. Figure 2(a) shows the areas with different bands of altitudes identified using only the SIDs and IAPs, and Figure 2(b) shows how several bands of altitude were not available without ATC providing wake advisories when the historical tracks were considered. The pointers show how the design of the corridors in Figure 2a presumed higher altitudes available for UAM operations whereas the altitudes had to be lowered as shown in Figure 2b.

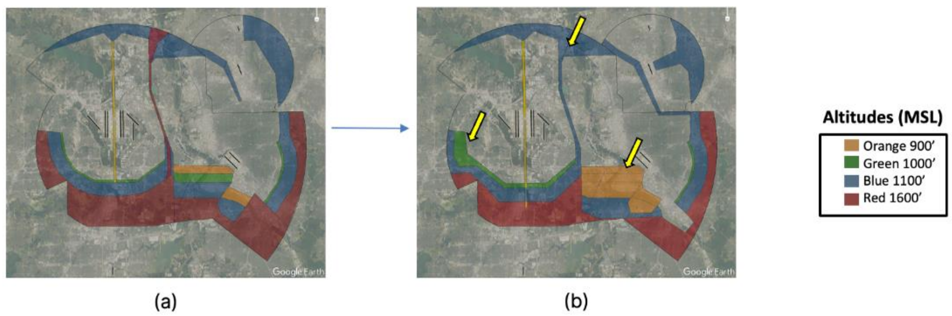

Fig. 1 Airspace identified for UAM operations in Class Bravo and Delta using (a) Published Instrument Approach Procedures (IAP) and Standard Instrument Departures (SID) and (b) historical tracks data

D. Use Cases

There were six UAM use cases that were investigated, they are listed below. These use cases were built from a set of use cases that had been generated with feedback from FAA in 2021 [5] The use cases on Airport Transfer to DAL and DFW will be described in detail this paper, the rest of the use cases have been described in detail in [10]

1) UAM Flights primarily in Class G/E: These required minimal ATC interaction and were routes between the vertiports listed outside of Class Bravo as per Table 2.
2) Entry and exit of Class Bravo: This use case includes a route between Denton and Dallas Downtown that is in Class Bravo. The LOA defined the route, and the pilot requested the coded route under Initial operations condition whereas the pilot simply entered the corridor in the Mid-Term operations conditions without any verbal clearances from the controller.
3) Airport Transfers: These use cases were focused on flights that had DAL or DFW terminal areas as their origin or destination. This use case is described later in more detail.
4) Flights inside Class B: These UAM flights followed the altitudes and speeds defined in the LOA. They either requested the coded route or had no verbal communication with ATC depending on the condition - Initial or Mid-Term operations respectively. Since the route/ corridor (see Figure 3) was in the airspace identified for UAM operations (Figure 2), no further communication with ATC was required.
5) Airport Periphery. There were two locations defined that served this use case. The flights destined for DAL Biz Jet location was on the periphery of DAL and the procedures resembled entering Class Bravo and landing at this location with minimal ATC interaction. The second location was on the periphery DFW at the vertiport DF7 (Fig. 3). Again, procedures here resembled entering class Bravo and landing at a vertiport located inside Class Bravo.
6) Flights parallel to runway arrival/departures: The use cases involved flying parallel to Spine Road in DFW and landing at a DF120 vertiport located on the parking garage of Terminal E of DFW. This use case is also defined in greater detail in the following sections.

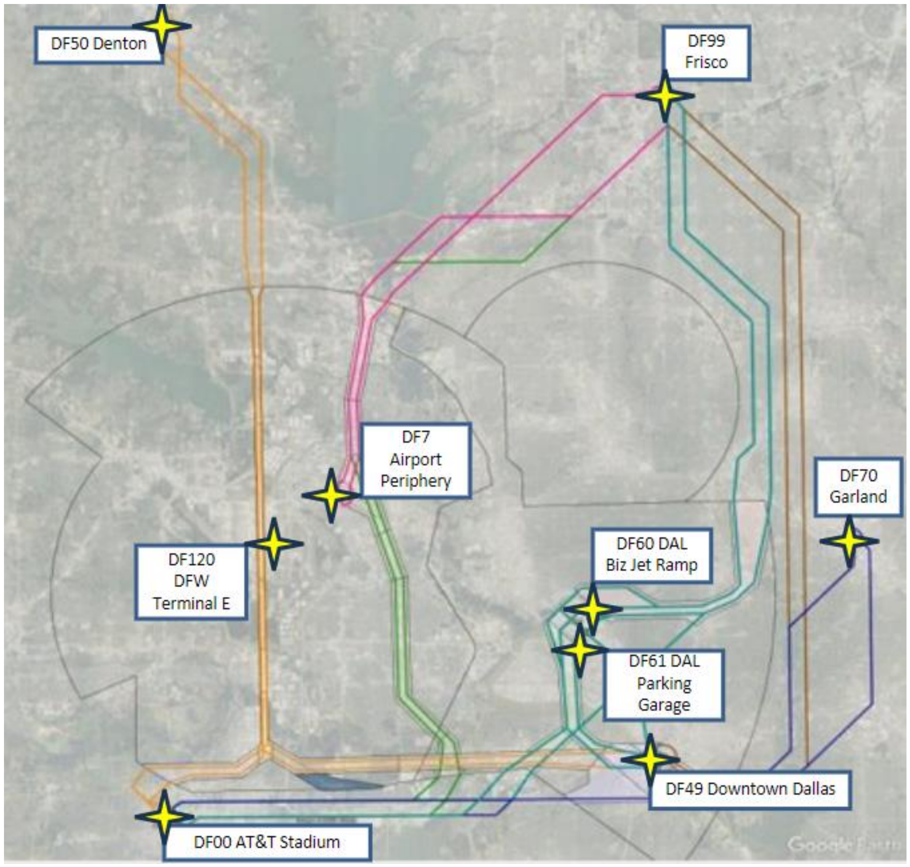

Fig. 3 Vertiport locations used in the simulation, the numbers point to the use case

1. Procedures for flights arriving or departing from DAL Parking Garage

In the initial operation condition, when pilots flew from Frisco (DF99) to the DAL Parking Garage (DF61) (Fig. 4), the PIC contacted the DAL Helo controller at GRNVL and per the LOA requested the specific coded route. DAL Helo would either approve the route or delay entry into Class B if necessary. Prior to KELTN, DAL Helo would handoff to the DAL Local controller and instruct the pilot to transfer to the appropriate frequency. Arrivals and departures to/from DF61 are affected by traditional traffic arriving and departing both runways since DF61 is located between the two runways (13R and 13L). Therefore, responsibility for the UAM aircraft is transferred from DAL Helo to DAL Local because the latter controller is also managing the runway traffic. For the UAM aircraft approaching DF61, two routes were available, either via APEST (approach end) or via MDEST (mid-field). DAL Local decided the route for the UAM aircraft based on the traffic approaching and departing from runways 13L and 13R. In most cases, the controller directed flights to cross the approach ends of the runways i.e. via APEST.

The inverse route departed from DAL Parking Garage (DF61) and arrived at Frisco (DF99) (Figure 4). The PIC contacted DAL Helo and requested the specific coded route. Departure from DF61 required initial route clearance from DAL Helo. For the departure, two routes were available, the first via ROPER, which would require coordination with DAL Local for runway crossing, or the second via SIGMA, which was a low-level (300 ft AGL) straight-out route parallel to runway departures. In most cases, the controller approved the flight via SIGMA, which required the aircraft to depart straight out of the vertiport and then make the turn for the next intermediate waypoint (SIGMA) joining the route. The aircraft followed LOA procedures for traversing the route and exiting Class Bravo.

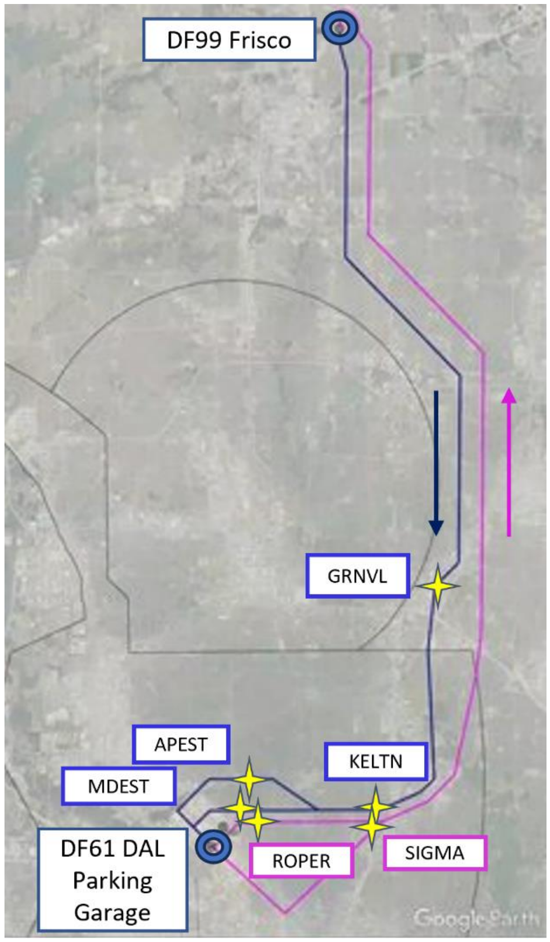

Fig. 4 Routes for DAL Parking Garage (DF61) to Frisco (DF99) (magenta) and Frisco (DF99) to DAL Parking Garage (DF61) (navy).

For Mid-Term operations, flights from Frisco (DF99) to the DAL Parking Garage (DF61) required the aircraft to squawk a 1207 beacon code at or prior to GRNVL and monitor the DAL Local frequency. Prior to GRNVL, when in Class E or G airspace, aircraft squawked the standard 1200 code. ATC observed the flight entering the Class Bravo UAM corridor, with the 1207 squawk code indicating the pilot's intentions to follow the LOA procedures. At or prior to the coordination point of KELTN, the PIC then contacted DAL Local, who is responsible for runway crossings. The DAL Local controller had the discretion to clear the aircraft for either the MDEST or APEST approaches, with the standard crossing being at APEST. For both approaches, the pilot is required (per the LOA) to announce when approaching MDEST or APEST. If they do not receive a clearance from DAL Local to "continue" across the runway, they would hold east of the approach end of the active runway. When conditions are appropriate, the DAL Local controller would clear the pilot to cross runway 13L for approach to the DAL Parking Garage (DF61).

Operating on the return route (i.e., DAL Parking Garage (DF61) to Frisco (DF99)) required the aircraft to squawk a beacon code of 1207 prior to departure because the route is partially contained within a corridor. The PIC contacted DAL Helo to request the specific coded route. DAL Helo was responsible for providing the departure clearance from DF61. Two routes were available, the first via ROPER, which required coordination with DAL Local for runway crossings or the second, via SIGMA, which was a low-level straight-out route. In most cases, the controller approved the flight via SIGMA, which required the aircraft to depart straight out of the vertiport and then make the turn for the next intermediate waypoint (SIGMA) joining the route (see Fig. 4). The aircraft followed LOA procedures for traversing through the route and exiting Class Bravo and did not talk to either the Local or Helo controller after being cleared on the route.

2. Procedures for flights parallel to runway arrivals and departures

In Initial operation condition, flights occurred between Downtown Dallas (DF49) and DFW Terminal (DF120) (Fig. 5). Prior to the departure, PIC contacted DAL Helo and requested the specific coded route that they planned to fly. DAL Helo would either approve the route or hold the aircraft for release (delay) as necessary. Once airborne per the LOA, the PIC contacted DAL Helo at or prior to BECKL. Next, DAL Helo would initiate a hand-off and transfer communications to DFW Helo. When advised the PIC would contact DFW Helo and continue rest of the route via Spine Road. There was no communication required between PIC and DFW Helo, while the UAM aircraft flew Spine Road. PIC adhered to all landing procedures as defined in the LOA and was delegated visual separation by the ATC as they got closer to the vertiports.

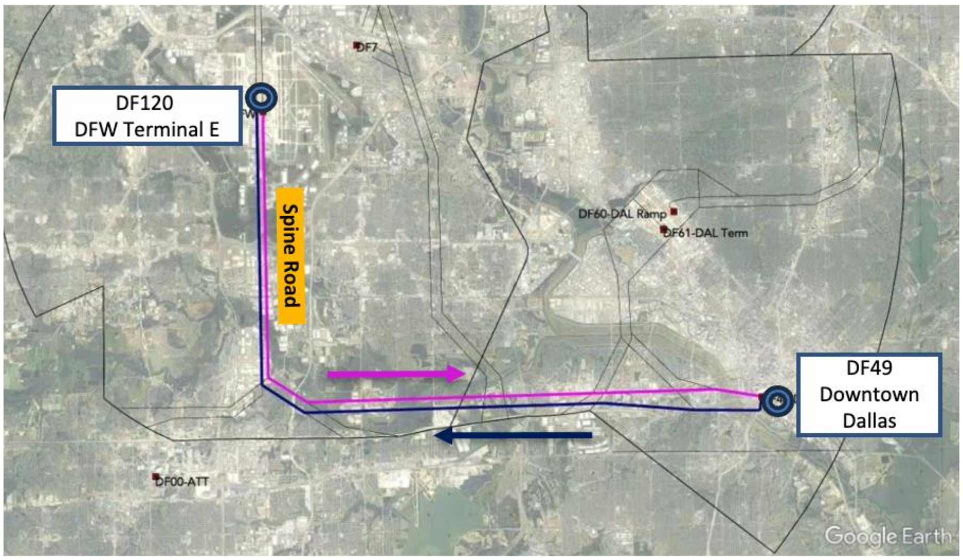

Fig. 52. Routes between Downtown Dallas and DFW Terminal E

The return route is from DFW Terminal (DF120) to Dallas Downtown (DF49). As per the LOA, the PIC contacted DFW Helo and requested the specific coded route they planned to fly. DFW Helo would either approve the route or hold the aircraft for release (delay) as necessary. Once airborne, per the LOA, the PIC would contact DFW Helo at or prior to BRAVO. As the aircraft approached the airspace that is the DAL Helo responsibility, DFW Helo would effect a hand-off and communication transfer to DAL Helo. Once instructed, the PIC would contact DAL Helo and continue flying the rest of the route.

In the Mid-term condition, flights departing from DFW Terminal (DF120) to Downtown Dallas (DF49) the PIC squawked 1207 prior to departure. In the Mid-Term condition, no explicit departure clearance was required for DF120 because it is located within as corridor. Once airborne the PIC monitored DFW Helo frequency at or prior to BRAVO. Downstream at an identified waypoint as per the LOA, the PIC would switch to the DAL Helo frequency and monitor it for the remainder of the flight. Flights departing Downtown Dallas (DF49) per the LOA, the PIC squawked 1207 prior to departure. Once airborne the PIC monitored DAL Helo frequency at or prior to BECKL. PIC switched to DFW Helo frequency at an identified waypoint as per the LOA and monitor the same frequency for the remainder of the flight.

E. Traffic Scenarios

The traffic scenarios involved two levels of UAM traffic. The low level of UAM traffic assumed a fleet size of 50 UAM aircraft and the UAM flights flew on the routes with a minimum of 1 nmi of in-trail spacing. The high level of traffic assumed a fleet size of 100 UAM aircraft and the aircraft flew with a minimum of 0.5 nmi of in-trail spacing. All UAM flights started at their origin vertiport and had a turnaround time of 10 min before they departed. They flew at enroute speed of 130 knots, approach and turn speeds ranged from 50-70 knots, with a maximum bank angle of 30 deg. Table 3 shows the composition of traffic to different locations as well as the level of background traditional traffic, which was kept constant in all the scenarios. The legacy traffic as shown in Table 3 represents a typical South Flow traffic over 40 min period at DFW and DAL: airports. Other small general aviation traffic was also added to the traffic scenarios, they were allowed to and often did cross the routes and corridors that were defined for this study.

Table 2. Traffic Levels Across Conditions Including Arrivals and Departures

Type of Flight		Arrivals	Departures	Total
UAM – Low Traffic	DFW Vertiports	25	21	46
	DAL Vertiports	16	16	32
	Dallas Downtown	19	15	34
UAM – High Traffic	DFW Vertiports	41	29	70
	DAL Vertiports	28	26	54
	Dallas Downtown	21	27	48
Legacy	DFW (17R, 17L, 17C)	29	48	77
	DFW (18R & 18L)	22	23	45
	DAL (13R & 13L)	28	15	43

IV. Results

Several objective and subjective metrics were collected for this research effort during the data collection period. in September 2023. Primary metrics included total traffic managed by different controller positions, arrival, and departure rates at vertiports, workload assessments (using a workload assessment keypad (WAK)) [11], and duration of pilot-ATC voice communications. WAK is used to collect subjective workload, where participants provide a digital input every five minutes on a scale of 1 to 5, where 1 corresponds to low workload and 5 to high workload. Other subjective measures included acceptability of procedures, routes, corridors, and information provided to the users. For a complete list of metrics and results refer to this publication [10]

A. Total Traffic Managed and Workload Reported in Class Bravo

Total traffic managed by different positions at DAL and DFW inside Class Bravo airspace will be described here along with the workload reported using the workload assessment keypad (WAK) [11]. The total traffic managed and reported workload are depicted for each minute of the simulation run, which were 45 min long.

Figure 6 shows the traffic managed inside Class Bravo Airspace for DAL Helo controller position for both Initial and Mid-term conditions. DAL Helo position managed UAMs and all General Aviation (GA) traffic in the Dallas Love Field sector. The level of traffic managed across both the conditions is similar, but the workload reported as shown by the line graphs shows that the workload reported for Initial operations condition was mostly under 3 on a scale of 1 to 5 (where 1 is low and 5 is high), whereas it was below 2 for Mid-term operations condition. The workload reported seems manageable and acceptable in both the conditions. As expected, the level of workload reported (shown by darker shade of line graph) is higher for the higher level of UAM traffic in both Initial and mid-term conditions, but the difference between high and low traffic is much smaller in the Mid-Term condition.

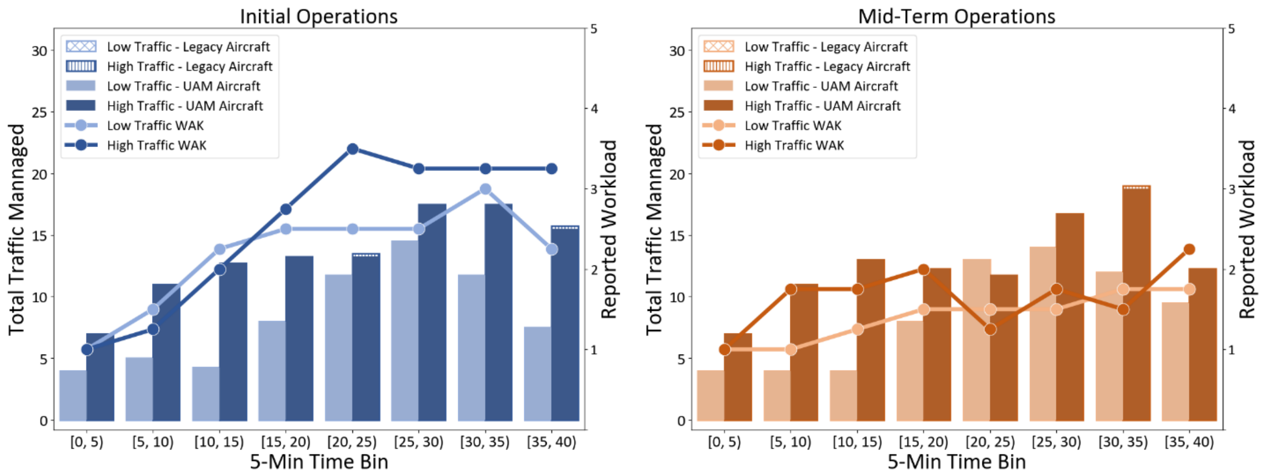

Fig. 63 Total traffic managed, and workload reported in Class Bravo for DAL-Helo, DAL Helo position across Initial and Mid-Term conditions.

Figure 7 shows the traffic managed inside Class Bravo airspace for DAL Local position for both Initial and Mid-Term conditions. The level of UAM and legacy traffic managed across both the conditions is similar, but the workload reported as shown by the line graphs indicates that the workload reported for both the Initial and Mid-term operations condition was about the same, almost always under 3 on a scale of 1 to 5. The workload reported seems manageable and acceptable in both the conditions. As expected, the level of workload reported (shown by darker shade of line graph) is higher for the higher level of UAM traffic in both Initial and Mid-Term operations conditions. The level of workload reported by this position does not show many changes between the Initial and Mid-term conditions since they are managing the same level of legacy traffic and handling all UAM arrivals to DAL parking garage that require crossing runways as described in the use case section, neither category of which benefit from corridor operations.

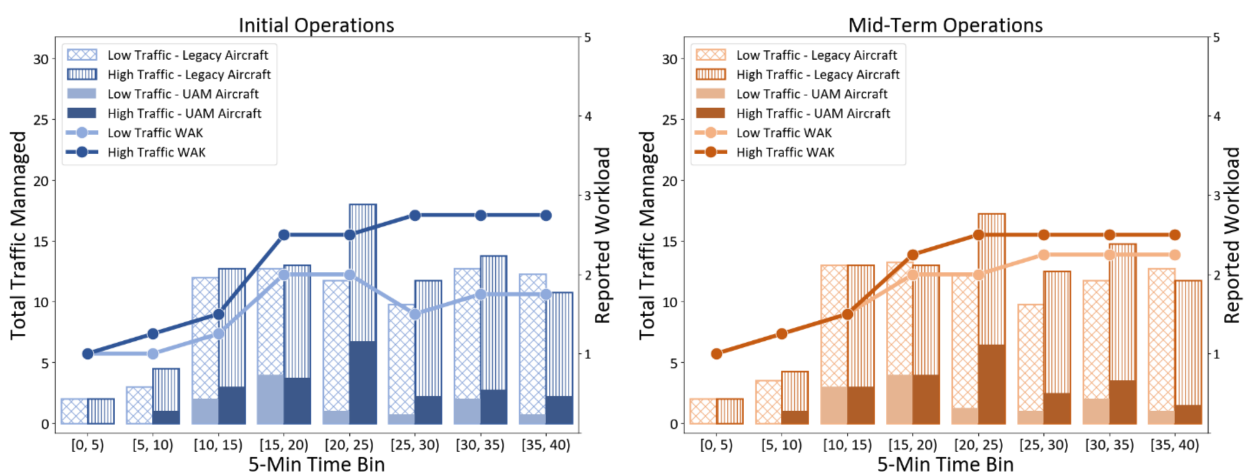

Fig. 74 Total traffic (UAM and legacy) managed, and workload reported in Class Bravo for DAL Local position across Initial and Mid-term conditions.

Figure 8 shows the traffic managed inside Class Bravo airspace for DFW Helo position for both Initial and Mid-Term conditions. The level of traffic managed across both the conditions is similar, but the workload reported as shown by the line graphs shows that the workload reported for the Initial condition was mostly around 3 on a scale of 1 to 5, whereas it was reported as 1 for the Mid-term condition. The workload reported seems manageable and acceptable in both the conditions. As expected, the level of workload reported (shown by darker shade of line graph) is higher for the higher level of UAM traffic in the Initial operations condition. No difference is seen between workload in the low vs high traffic conditions in the Mid-Term because workload overall was very low in both.

Figure 9 shows the traffic managed inside Class Bravo airspace for DFW Local East position for both Initial and Mid-Term operation conditions under the two traffic levels. DFW Local position did not manage any UAM traffic, they were responsible for traditional traffic operating to the primary runways (17C and 17R). Thus, the level of traffic controllers managed is the same for both Initial and Mid-Term conditions and the workload that was reported is nearly identical across all conditions and traffic levels. They did not report being impacted by UAM traffic that used the Spine Road between the East and West complexes of DFW.

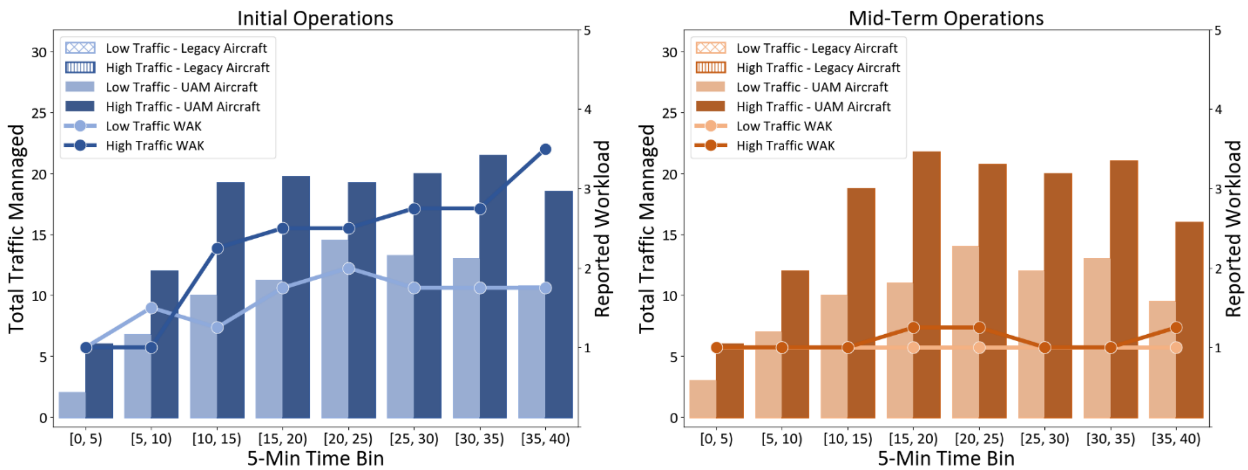

Fig. 85 Total traffic managed, and workload reported in Class Bravo for DFW Helo position across Initial and Mid-term condition.

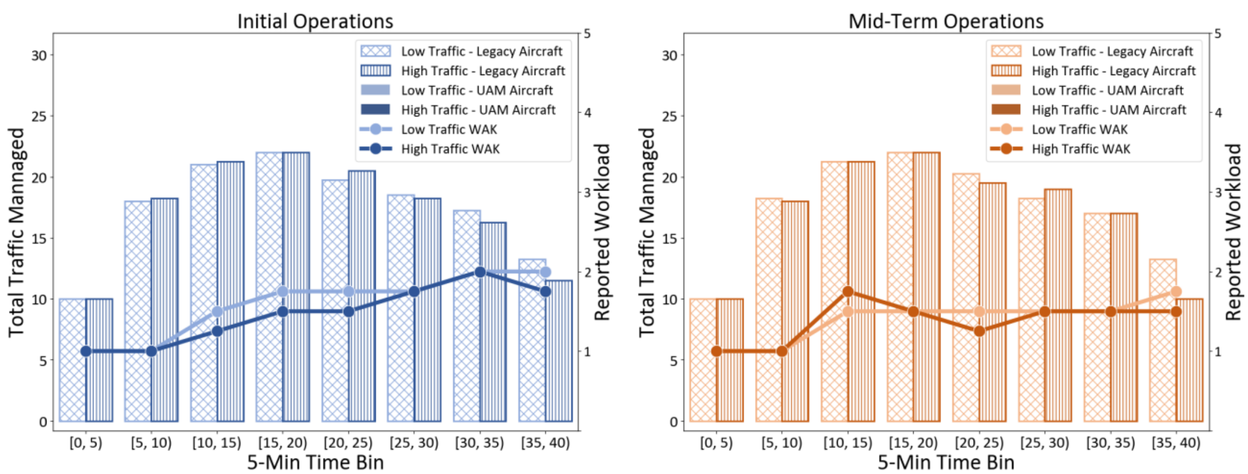

Fig. 96 Total traffic managed, and workload reported in Class Bravo for DAL Local position across Initial and Mid-term condition.

B. Total Number of UAM operations to Vertiport

The number of UAM operations to respective vertiports of interest DAL Parking Garage (DF61) and DFW Central Terminal (DF120) are discussed for the two controller positions DAL Helo and DFW Helo. In addition to the total number of UAM operations, specific numbers for arrivals and departures to both vertiports will be discussed. Figure 10 and Table 4 show the number of UAM operations to the DAL parking garage (DF61). Notably, the number of UAM operations peak around 5-7 within a 5-min bin and are relatively consistent across operational conditions. The average number of operations per hour was extrapolated by (multiplying the total number of operations in a 40 min by 1.5 to get hourly rates) to be around 24-40 UAM operations per hour for the DAL parking garage under low and high traffic levels respectively, for both conditions.

Figure 11 and Table 4 show the number of UAM operations for the DFW Central Terminal, DF120. Here the peak numbers are again relatively similar between operational conditions. However, there is a peak of around 9 in a single 5-Min bin in the Initial operations. The hourly rate at DFW central terminal was again extrapolated (by multiplying with 1.5) and found to range from 43-55 UAM operations per hour for the low and high traffic levels, respectively. The level of workload reported by DFW Helo position was reported as manageable and acceptable in the previous section. This provides the indication that the outlined procedures were feasible under nominal conditions.

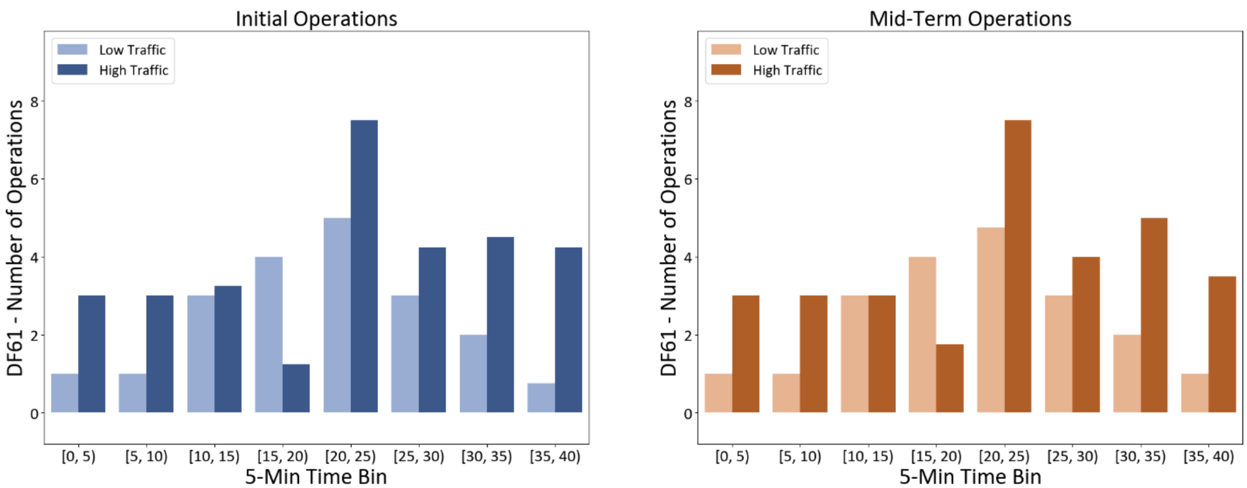

Fig. 107 The total number of UAM operations at DAL Parking Garage (DF61).

Table 4: Average Number of UAM operations over 40 min period

	Initial Operations		Mid-Term Operations	
	Low Traffic	High Traffic	Low Traffic	High Traffic
DFW Vertiports				
DFW Central Terminal	29	37	29	37
DAL Parking Garage	16	26	16	27

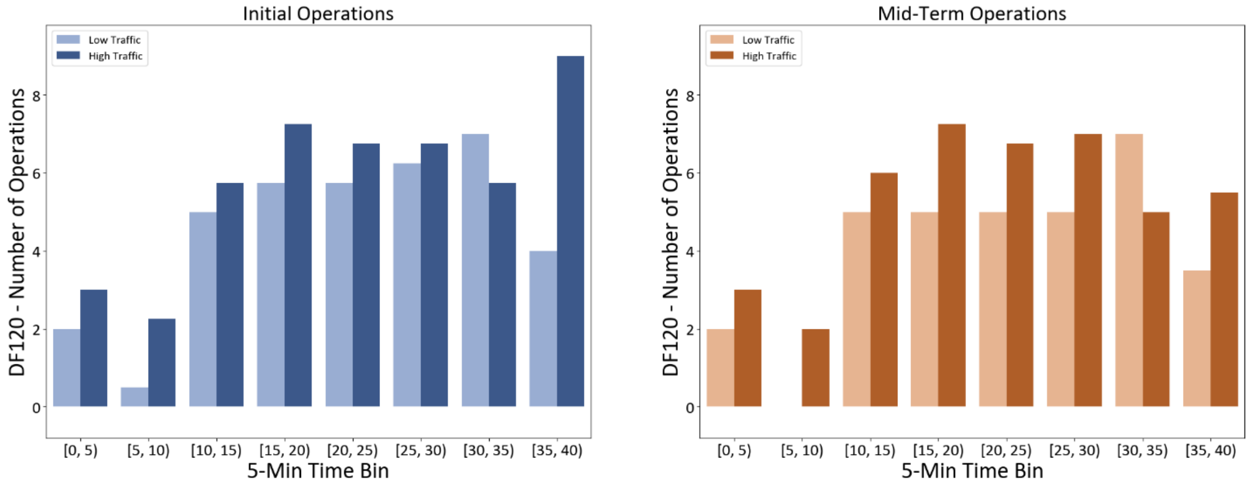

Fig. 118 Total number of UAM operations at DFW Central Terminal (DF120).

C. In-trail Spacing between UAM arrivals

This section describes the in-trail spacing between arrivals only to the two central terminal area vertiports. Flights arrived to the DFW central terminal area traveling either north (which are referred to as "north arrivals" coming from the south) or south (referred to as "south arrivals" coming from the north). The time in-trail spacing between the aircraft is shown for the two approach directions to DFW Central Terminal in Table 5 and Table 6. The average time-in-trail between the south arrivals is much longer (approx. 20 min in low traffic and 10 min high traffic) since there were more arrivals coming from north. Time-in-trail for north arrivals is 2.5 min in the low traffic scenario and 1.6 min in the high traffic scenario (Table 6) for both operational conditions (Initial or Mid-term).

Table 7 shows the average time-in-trail spacing under different conditions for flights going to the DAL parking garage. In the low traffic condition, the in-trail spacing is approximately 4 min and in the high traffic condition, it is approximately 2 min for both operational conditions (Initial or Mid-Term operations). The runway crossings required to access DAL parking garage increase the in-trail spacing between UAM arrivals and decrease the rate of arrivals when compared to DF120 vertipads located on DFW Central Terminal, which do not require runway crossings. At The DAL parking garage location, the arrival and departure flights were managed by two different controllers and at DFW Helo position managed both UAM arrivals and departures.

Table 5. Average time in-trail (minutes): DF120 - South Arrivals.

	Initial Operations	Mid-Term Operations
Low Traffic	22.51	20.02
High Traffic	10.02	6.77

Table 6. Average time in-trail (minutes): DF120 - North Arrival

	Initial Operations	Mid-Term Operations
Low Traffic	2.46	2.52
High Traffic	1.62	1.67

Table 7. Average time in-trail (minutes): DF61 Arrivals.

	Initial Operations	Mid-Term Operations

Low Traffic	3.8	4.24
High Traffic	1.9	1.83

D. Delays (Ground and Airborne)

An objective metric that can indicate relative levels of controller workload is the delay that pilots receive in getting their clearances to depart a vertiport or enter a Class Bravo. When controllers are busy and workload is high, they take longer to respond to pilot requests for these clearances. However, there is no absolute value of delay that can be correlated to an absolute level of workload, instead relative delay values across experimental conditions indicate trends in relative workload levels. Both ground and airborne delays for DAL Helo and DFW Helo positions are reported.

DAL Helo experienced higher ground delay in the Initial operations condition due to frequency congestion as the controller was providing departure clearance to flights out of all three vertiports around Dallas Love Field airport and Dallas Downtown. In Mid-Term operations, the DAL Helo controller was still managing departure traffic for vertiports co-located on the airport, so delays are seen in that condition, but the delays are much shorter than in the initial operations condition. Ground delay is observed as longer for high traffic levels than low traffic levels for both operational conditions, as would be expected if frequency congestion is driving the delays (Fig. 12).

Mean airborne delay was otherwise negligible or zero for other time bins in both Initial and Mid-Term operations. These results are the product of the procedures where Initial operations condition required clearance for entering Class Bravo airspace and thus had some delay especially when traffic was high. However, Mid-Term operations did not require clearance into Class Bravo airspace UAM corridors and so no delays were reported for those operations.

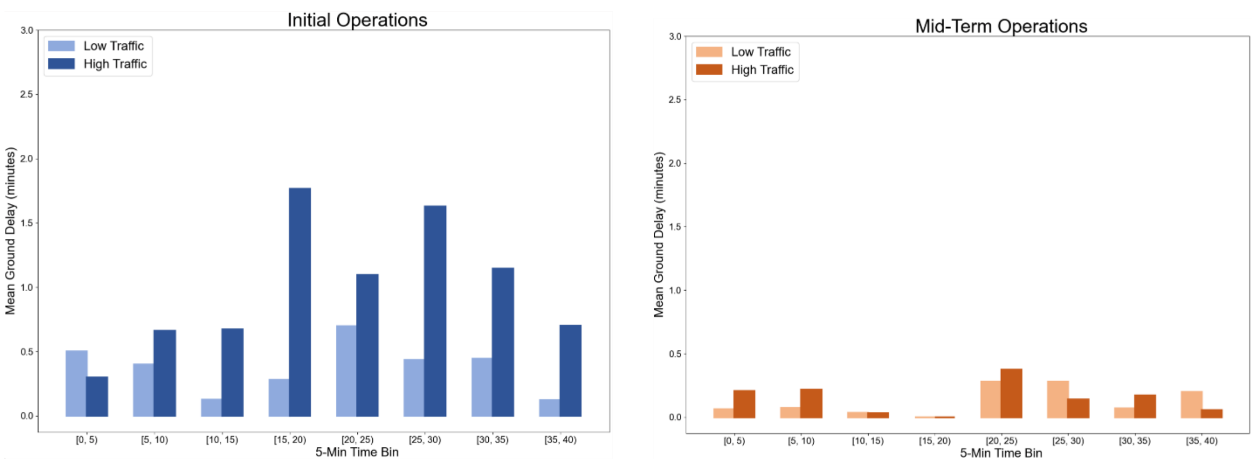

Fig. 129. Mean ground delay for UAM traffic managed by DAL Helo position.

Figure 13 shows the mean ground delay for DFW Helo and indicates that typical delays (up to 2 min) occur in the Initial operations condition since traffic throughput is bottlenecked due to frequency congestion. Again, this bottleneck becomes more significant for the higher traffic scenario (delays about 2 min). Similar to the DAL Helo position, the airborne delay was almost zero for both operational conditions and traffic levels. Together with the results for DAL Helo, these results indicate that the procedures used for Mid-Term operations were effective in eliminating ground delays for both positions, traffic levels, and operational conditions.

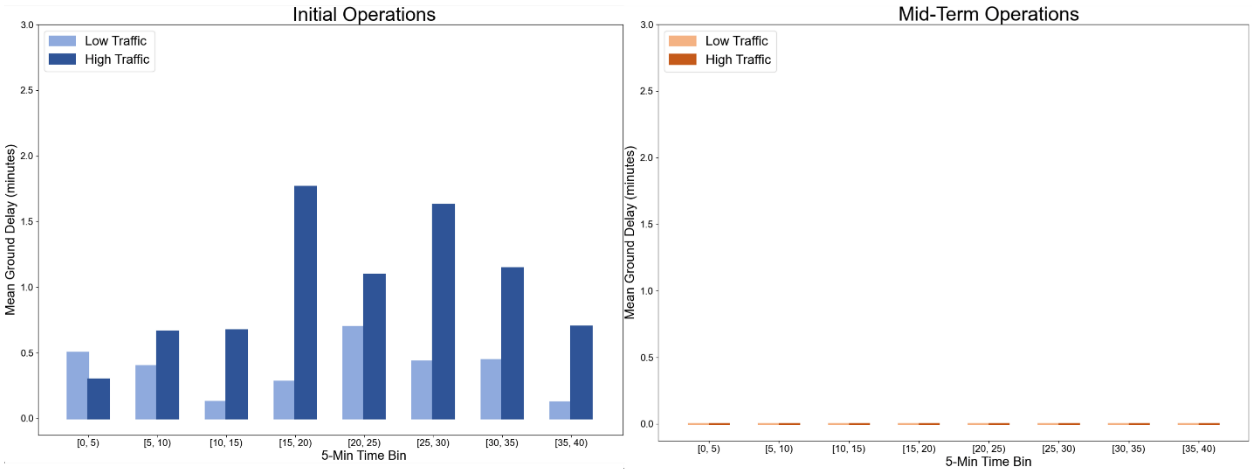

Fig. 1310 Mean ground delay for UAM traffic managed by DFW Helo position.

E. Communication – Count and Duration

An objective metric that can be directly tied to controller workload is the percent of time that pilots and air traffic controllers spend talking to each other out of the overall scenario duration. The time that controllers spend talking or listening to pilots is time taken away from their other responsibilities. The percentage of time spent communicating is shown in Fig. 1414 and correlates well with the workload results shown in Figure 6 and 7. The percentage of simulation run time the DAL Helo controller spent communicating with aircraft dropped substantially from 60% to 18% between the Initial and Mid-Term operations conditions in the high traffic condition. As with the WAK data, an even larger reduction was seen for DFW Helo, it dropped from 58% to below 4%. The DAL Local position controlled a mix of conventional and UAM traffic, communications did not appear to diminish in the Mid-Term condition because the UAM flights destined for DAL parking garage needed a runway crossing clearance from DAL Local (Figure 14). Communications procedures did not change for DFW Local since they manage conventional traffic only, hence no changes are seen between conditions and traffic levels (Fig. 15). The Mid-Term procedures appear to be very effective in reducing voice communications under nominal conditions and correlate well with reductions in workload.

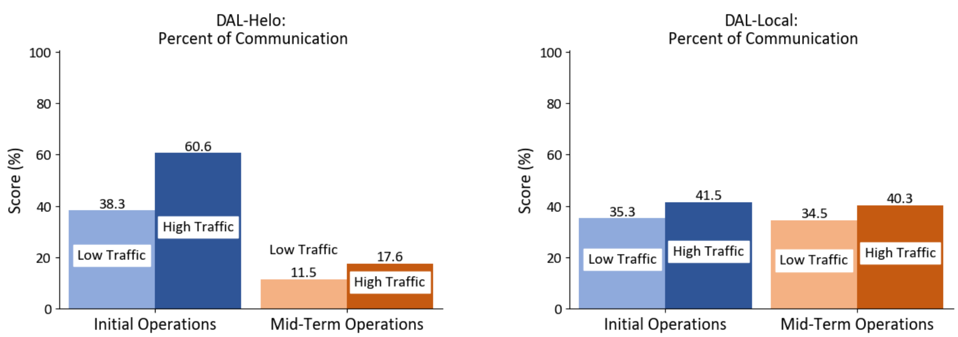

Fig. 14 Communication Results (Percent of Total Run Time) for DAL.

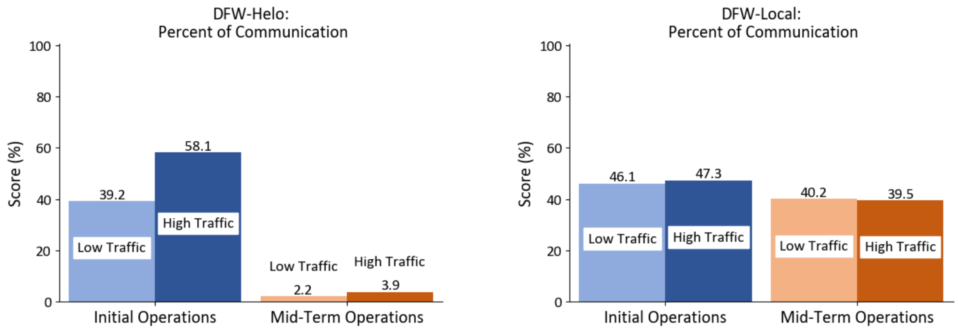

Fig. 1511 Communication Results (Percent of Total Run Time) for DFW

F. Acceptability of workload

The acceptability of the controllers' workload was measured in post-run surveys. As with the other workload metrics, all combinations of procedure conditions and traffic loads were rated generally acceptable (Fig. 16 and Fig. 17). Workload was reported as manageable by the DAL Helo (Fig.16) and DFW Helo (Fig. 17) positions under low traffic loads for Initial operations, but the level of reported acceptability decreased in the high traffic condition. The results for low and high traffic in the Mid-Term condition for both DFW and DAL Helo positions were reported as highly acceptable (ranging from 4.0 to 5.0 on a scale of 1 to 5, where 1 is low acceptability and 5 is high acceptability). The mix of conventional and UAM traffic at DAL Local was rated moderate to high in acceptance for both conditions and traffic loads (Fig. 1612). DFW Local (with all conventional traffic) showed high acceptability of workload (Fig. 1713). The Mid-Term procedures appear to be very effective at improving the acceptability of workload under nominal conditions compared with the Initial operations procedures.

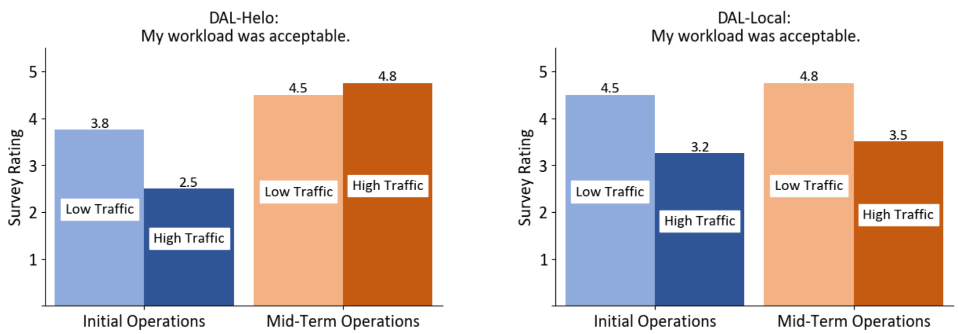

Fig. 1612 Acceptability of workload for DAL.

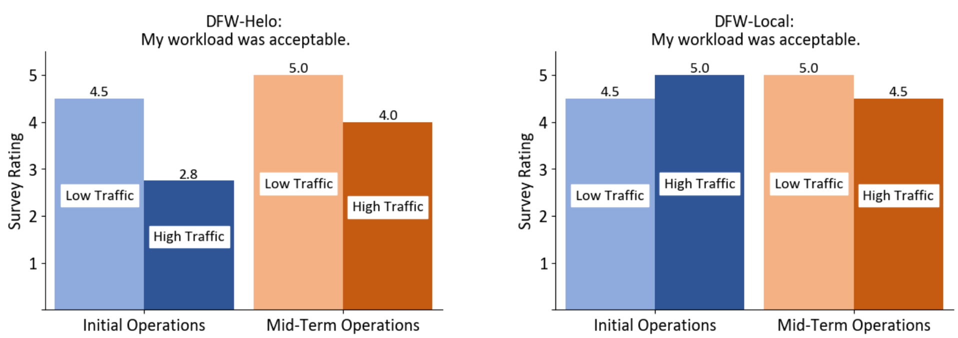

Fig. 1713 Acceptability of workload for DFW.

G. Acceptability of Procedures

Effective procedures are one of the primary ways to ensure safe and efficient UAM operations. To evaluate the acceptability of airspace procedures, post-run survey questions regarding the adequacy of procedures and their effect on workload were developed and administered. Controller's responses were recorded during both Initial and Mid-Term operations, and the data provides further insights. The following ratings provided by the controllers on survey questions, with ratings that range from 1 to 5, where 1 is low and 5 is a high rating. **Error! Reference source not found.** and **Error! Reference source not found.** show that the procedures were generally acceptable across all traffic loads and conditions with relatively high ratings (4.0 and greater) for controllers operating the DAL Helo and DFW-Helo positions during Mid-Term operations.

In contrast, the DAL Helo controller under Initial operations and high traffic levels indicated that procedures were challenging and did not reduce workload (Fig. 18). They provided similar ratings for routes and airspace affecting their workload (Fig. 20)

DAL Local provided relatively higher rating for Mid-Term than Initial term operations on the survey questions regarding procedures lowering their workload (Fig. 18) and UAM routes lowering workload (Fig. 20). However, similar to the DAL Helo position, they also reported the procedures as challenging and UAM routes not helping reduce workload considerably under Initial operations, high traffic conditions.

DFW Helo position (Fig. 19 and Fig. 1915) reported that procedures as well as for UAM routes and corridors helped reduce their workload with ratings that were 4 or higher for Initial operations irrespective of traffic. DFW Local had high ratings for all the above-mentioned survey questions since they do not directly manage UAM traffic.

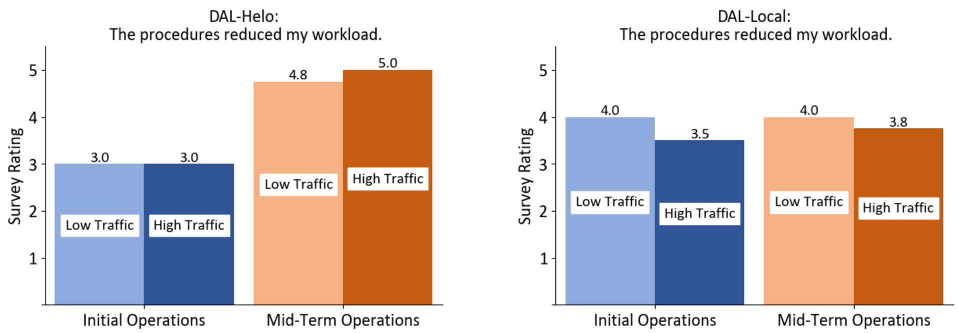

Fig. 1814 Survey responses regarding the effects of airspace procedures on workload for DAL.

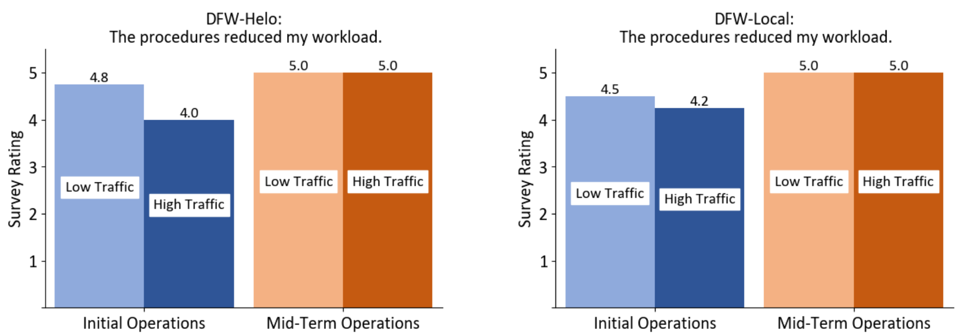

Fig. 1915 Survey responses regarding the effects of airspace procedures on workload for DFW.

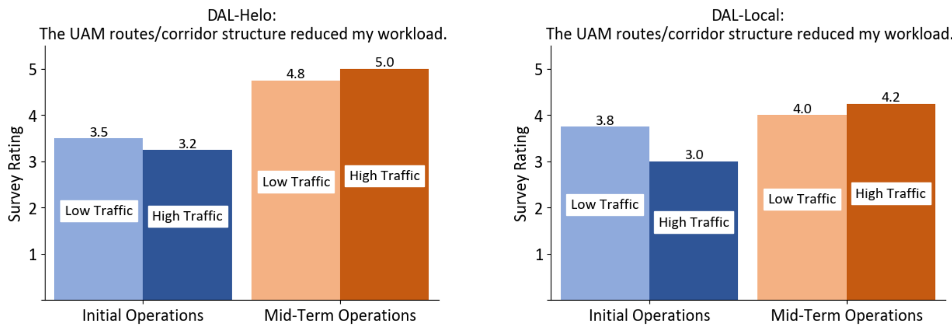

Fig. 2016 Survey responses regarding routes, corridors and workload for DFW.

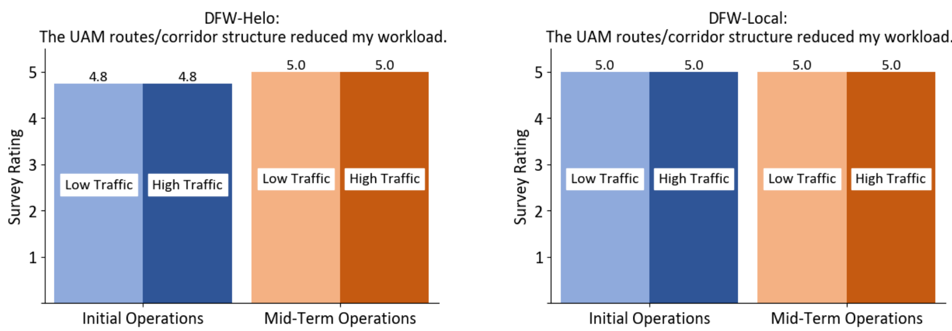

Fig. 2117. Survey responses regarding routes, corridors and workload for DFW.

V. Discussion

The objectives of this research were to test procedures between ATC and pilot in command, or PIC, for Initial and Mid-Term UAM operations. The UAM operations to the vertiports on DAL parking garage (DF61) and DFW Central Terminal (DF120) were of the most interest. It was found that the total traffic managed by the Helicopter positions at DAL and DFW was similar between the Initial and Mid-Term operations conditions. However, there was a difference between the workload reported during the run via WAK for both DAL and DFW. The workload was reported relatively higher for the high traffic conditions but was sporadic in nature, the workload reported stayed at manageable levels for sustained periods of time.

DAL Helo position managed UAM arrivals and departures off the DAL parking garage located between the runways. The procedures designed for this vertiport required the DAL Helo to handoff the UAM arrivals to the DAL Local position during initial operations, who ensured safe runways crossings for the UAM arrivals. The procedure was modified for Mid-Term operations where the UAM pilot did not need to check-in prior to entering the Class Bravo corridor but needed to check in with DAL Local directly to get a clearance to get to DF61 either via approach end or mid-field of 13L or 13R runways. The DAL Local preferred to cross the UAM via the approach end and commented that they would like the procedures for the arrivals from east and west to be staggered over the approach end of the traditional traffic. Thus, the DAL local reported similar levels of workload between Initial and Mid-Term operational conditions whereas DAL Helo who was managing only UAM departures during Mid-Term operations reported a reduction in workload. Workload increased with increasing traffic level and complexity for DAL Local, because they had to control runway crossings but remained the same between Initial and Mid-Term conditions.

UAM departures out of DF61 stayed with DAL Helo, who took them straight out before they turned to join the route or corridor depending on initial or Mid-Term operations respectively. The percent of communication for DAL Helo reduced from 60% to 18% between initial to Mid-Term operations for high traffic condition. The arrivals and departures in and out of DF61 were regular ATM operations and required communicating with the controller due to the location of the vertiport that required runway crossings, which was not the case for DFW.

DFW Helo controllers reported a higher reduction in workload between initial and Mid-Term operations. This can be contributed the level of communications that was reduced from 60% to 4% under high traffic conditions for initial to Mid-Term operations for DFW Helo. This is dramatic reduction in communications and is supported by the workload reported by this position both using the WAK (around 1 out of 5).

The UAM operations to DFW Central Terminal utilized Spine Road. The Spine Road is a road that separates the east and west complex of DFW and is a published helicopter road. Under nominal operations, when there are no traditional flights crossing the Spine Road between the two complexes, participants of our table-top exercise conducted in June 2023 informed us that they fly regularly at 300 ft AGL with minimal communications. The participants commented that the operations on Spine Road that do not require any runway crossings have a high likelihood of becoming a successful corridor (Mid-Term operations) under VMC flying VFR. Controller participants also mentioned that controllers will "need to trust the procedures" for Mid-Term operations where there were practically no communications with the pilots. Reported workload did not change for the DFW Local position between Initial or Mid-Term operations, which is a nice validation because their traffic load (traditional traffic) didn't change, because there was no change observed in their responsibilities.

The number of operations planned to DFW and DAL vertiports was also reported. The peak number of operations in a 5 min period at DAL parking garage was 6 operations and 9 operations at DFW under high traffic conditions. The in-trail spacing between the UAM arrivals was approx. 2 min for DAL parking garage and 1.6 min for DFW Central Terminal vertipads dedicated to north arrivals. DFW controllers provided positive feedback on UAM flying Spine Road as a route as well as corridor. They mentioned that operations under Mid-Term condition where communications were not required to enter the corridor, or for landing and departures, it was easier to pay attention to the traditional traffic in and around DFW. However, they also noted that monitoring aircraft can get monotonous and suggested clicking on a UAM arrival when it enters the corridors as a way of acknowledging it.

It was also observed that UAM flights experienced ground delays under the initial condition only for both DAL and DFW Helo positions. This is the case because in the Initial operations condition, UAM pilots require a departure clearance to get airborne. There is some ground delay also observed for DAL Helo position during Mid-Term condition because vertiports located between the runways on DAL (DF61) still required a departure clearance whereas that was not the case with DFW departures due to their location being closer to the Spine Road. The DFW Helo position did suggest that since the departures just popped up on their screens under the Mid-Term condition, they would like to see a predicted departures-list for the UAM flights planned to take off from DFW Central Terminal.

The DAL Helo position reported relatively lower acceptability of routes and procedures for the Initial operations because the roles and responsibilities of the controller in the Initial operations do not change drastically whereas the operator is responsible for managing aircraft inside new airspace structures for Mid-Term operations, which changes the workload experienced by the controller participants in the Mid-Term operations condition. DAL procedures were unique for Mid-Term since the new airspace structures were not applicable over the airport and regular ATC communications were expected.

DAL Local position does not show much difference between Initial and Mid-Term operations on acceptability of procedures. They provided relatively lower ratings for acceptability of their workload under high traffic condition for both Initial and Mid-Term conditions. This makes sense because the amount of traditional and UAM traffic they had to communicate with was the same in the two conditions. The procedures for UAM arrivals during Mid-Term required that they contact DAL Local directly without first contacting DAL Helo.

DFW positions report high levels of acceptability on the impact of procedures and routes and corridors on their workload. Their UAM operations did not require crossing approach end or runways, thus making the nominal operations on Spine Road more feasible and scalable than those destined for DAL Parking garage.

VI. Summary

This study successfully investigated procedures, communications, and information requirements for UAM traffic during Initial and Mid-Term operations. It uncovered that procedures and LOAs can be powerful tools that can help scale the operations up to nine arrivals or departures at an airport terminal over a five-minute period and average rates up to 55 operations per hour when UAM aircraft do not need to cross runways and 40 operations per hour when UAM aircraft do need to cross runways. The procedures developed and tested provide a starting point for developing UAM procedures suitable for other airports with similar configurations. For example, procedures for crossing runways to access the DAL parking garage can be applied to similar vertiport locations at other airports such as Los Angeles International with its four parallel runways or John F. Kennedy with its dual parallel runways. The study only investigated airspace factors and nominal operations and did not constrain vertiport capacity. Hence the researchers suggest further exploring off-nominals and more complex demand and capacity balancing functions that are expected to be necessary to generate the flows of traffic modeled in this simulation.

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