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Exploration of Near-term Potential Routes and Procedures for Urban Air Mobility

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This paper investigates routes and procedures for Urban Air Mobility (UAM), which aims to reduce congestion on the roads and highways by offering air taxi as an alternative to driving. The routes and procedures being explored are current-day helicopter routes along with different communication procedures that are available as tools in the near-term. Three different levels of UAM traffic were evaluated in the Dallas Fort Worth (DFW) area. The current-day helicopter routes were modified to separate them from traditional traffic, and a Letter of Agreement (LOA) was introduced in some of the conditions to reduce verbal communications. We found that modifications to the routes and introduction of LOA helped increase the number of UAM flights that the controllers reported they could manage and reduce their communications, which made controller self-reported workload more operationally acceptable. However, the self-reported workload experienced by busy airport towers cannot be effectively managed via the usage of LOA and modified helicopter routes, suggesting there is an opportunity to re-think roles and responsibilities of the UAM system participants.

I. Nomenclature

AGL	=	Above Ground Level
ADS	=	Addison Airport
ATC	=	Air Traffic Control
DAL	=	Dallas Love Field Airport
DFW	=	Dallas Fort Worth International Airport
eVTOL	=	electric Vertical Takeoff & Landing
HITL	=	Human-In-The-Loop
IFR	=	Instrument Flight Rules
LOA	=	Letter of Agreement
MSL	=	Mean Sea Level
nmi	=	nautical miles
NAS	=	National Airspace
UAM	=	Urban Air Mobility
sUAS	=	small Unmanned Aerial Systems
UTM	=	UAS Traffic Management
VFR	=	Visual Flight Rules

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II. Introduction

The National Airspace System continues to grow in complexity and demand resulting in more delays and increased pressure on current resources. Recently, there has been a deluge of new entrants in the NAS that are putting more demands on existing facilities and resources. Most of the research in the United States and European Skies [1] related to the urban areas has focused on the new entrant small Unmanned Aerial Systems (sUAS) flights, their integration with the airspace, and building safe operations in densely populated areas. In the United States, NASA, the FAA, industry, and academia have been actively working toward the development and demonstration of a UAS Traffic Management (UTM) system for sUAS operations in low-altitude airspace [2]. Increasing road congestion has led to a growing interest in UAM. The goal of Urban Air Mobility (UAM) is to move people and cargo through metropolitan areas via safe and efficient air traffic operations [3,4]. UAM is expected to improve mobility for the general public, decongest road traffic, reduce transport time and reduce the strain on existing public transport networks [5,6].

There is a great deal of investment made by industry, government and academia who are researching Urban Air Mobility. Uber Elevate, one of the Industry partners, has published a white paper describing their vision for an air taxi service [4]. It includes an analysis of the feasibility of using electric Vertical Takeoff and Landing (eVTOL) vehicles for air taxi services, the economics of the air taxi market, and the ground infrastructure (e.g., vertiports, charging systems) required for air taxi operations. Additionally, it discusses several crucial airspace integration challenges for UAM, such as efficient sequencing and scheduling of eVTOLs into and out of vertiports (similar to heliport with several helipads) and interoperability between vehicles. There exist several other challenges to UAM, such as integration of procedures with existing airspace and the airport, noise levels that are acceptable to the general public, public safety, public acceptance, vehicle certification, and many more..

Previous studies on UAM have focused on fast-time simulations of the routes that are separated via a separation service and network of routes [7]. Similarly, research done collaboratively by US and Europe has also primarily been conducted using fast-time simulations and has focused on the approach profile for these innovative eVTOL aircraft, vertiports and battery life [8] and more. Other studies, including Market studies, have focused on the demand for UAM and population demographics who can afford air taxi, using surveys to estimate the commuter's willingness to pay for such flights [9].

In collaboration with partners and stakeholders over the next few years, NASA will develop detailed concepts of operations for UAM airspace integration at different stages of operational maturity. The evolution of the UAM operational concept is expected to start with low-tempo, low-density flights along with a set of fixed routes referred to as "Emergent operations." These operations will then morph into "Early Expanded UAM operations," characterized by higher-tempo, higher-density flights in a small network of vertiports feeding a common hub location and managed by UAM operators and third-party services. These will be followed by "Mature UAM operations," characterized by high-tempo, high-density flights in a network with multiple hub locations, potentially with orders-of-magnitude more vehicles and operations in an area that are currently supported in the NAS [5]. NASA is currently exploring how the UTM paradigm can be applied to UAM as concepts are being developed and evaluated. It is also expected that the following guidelines for UAM operations as part of the On-Demand Mobility [3] effort will need to be considered:

1. Does not require additional ATC infrastructure
2. Does not impose additional workload on ATC
3. Does not restrict operations of traditional airspace users
4. Will meet appropriate safety thresholds and requirements
5. Will prioritize operational scalability
6. Will allow flexibility where possible and structure where necessary

Since UAM operations are likely to occur in metropolitan areas that will require UAM flights to access controlled airspace (Class B, C and D) as also described in previous papers [5]. It is also likely that near-term UAM operations will be required to comply with current airspace rules and regulations and that they will be very similar to, if not the same as, current Visual Flight Rules (VFR) operations. Furthermore, it is expected that these initial UAM flights will be conducted by human pilots on board the UAM aircraft at all times and will have ATC providing services as in current operations [5]. This paper explores potential routes and procedures in a Human-in-the-Loop (HITL) experiment that could be applied in the near-term to allow integration of UAM flights into the airspace, as well as into a large airport. The purpose of this exploration is to help identify operational constraints and capabilities in current-day operations. The rest of the paper is organized as follows: Section III will describe the methodology used to explore these operations with a focus on airspace and experimental details and metrics planned for the study. Section IV will

focus on data analysis, Section V will provide a discussion of the results and Section VI will summarize, provide conclusions and next steps.

III. Methodology

The research focuses on designing and testing routes and procedures for UAM operations that access Class B, C and D airspace. As mentioned earlier, UAM operations will be expected to comply with current airspace rules and regulations. Since the test airspace of the Dallas Fort Worth area does not include a Class C airport, only Class B and D airspace procedures were investigated.

A. Experiment Matrix

The two variables explored in this research study were levels of traffic and routes with different communications. Three different communication procedures including Letter Of Agreements (LOA) were evaluated with three different levels of UAM traffic shown in Table 1

		Helicopter Routes		
UAM Traffic Level		Current Routes *Current Communications without LOA* **(Baseline)**	Current Routes *Reduced Communications with LOA*	Modified Routes *Reduced Communications with LOA*
	Low	Scenario C1	Scenario CL1	Scenario M1
	Medium	Scenario C2	Scenario CL2	Scenario M2
	High	Scenario C3	Scenario CL3	Scenario M3

Table 1. Experimental Matrix

1. Level of UAM traffic

The level of UAM traffic was varied across conditions, where low traffic was characterized by UAM flights temporally separated by 90 s, medium traffic at 60 s, and high traffic was temporally spaced at 45 s. Table 2 shows the equivalent enroute distance spacing of each traffic level assuming that all flights were flying at 130 knots, and the total number of flights simulated within a 40-minutes run to achieve each traffic level. Table 3 shows the number of traditional commercial flights utilizing Dallas Fort Worth (DFW), Dallas Love (DAL) and Addison (ADS) airports that were also included as background traffic in all the runs. This background traffic was kept constant across the different conditions.

	Low Traffic	**Medium Traffic**	**High Traffic**
Enroute Temporal Spacing	90 s	60 s	45 s
Enroute Spacing	3.75 mi	2.5 mi	1.875 mi
Total Number of Flights	115	167	225

Table 2 Definition of UAM Traffic Level

	DFW	DAL	ADS
IFR-Arrivals	54	16	6
IFR-Departures	50	20	1
VFRs (arrivals and departures)	0	1	11
Total	104	36	18

Table 3. Traditional Background traffic at the different airports simulated over the 40 min run

2. Routes and Procedures

The scenarios C1 to C3 in Table 1 refer to Baseline conditions, which use current-day helicopter routes as shown in Figure 1. The current-day helicopter routes are generally set along the highways for visual reference and have no speed or altitude restrictions. The communications involved in these conditions were the same as current-day, where the helicopter or UAM pilot needs to ask permission to enter Class B airspace from the air traffic controller prior to entrance and provide the full planned route or general intent. The controller is required to assign beacon codes, read back the entire route clearance, and ensure that this UAM traffic stays separated from the traditional traffic. The controller may make traffic calls for wake turbulence or for notice of other traffic to both helicopter or UAM pilot and traditional traffic when required.

The scenarios CL1 to CL3 in Table 1 refer to the Current Routes with LOA conditions, which used current-day routes with a newly introduced LOA that was meant to help reduce communication with the UAM flights. LOAs can help reduce verbiage, define the available routes precisely, and separate the routes from each other. The LOA made provisions for the UAM flight to have pre-assigned beacon codes to signatory operators who sign and agree to the terms of the LOA. It also created route codes or names for flights flying the same origin and destination pairs, which the signatories would use when entering Class B airspace. This would help reduce the verbiage involved in providing the full route description or flight intent on entry into Class B and D airspaces. In the CL1 to CL 3 scenarios, the current-day helicopter routes were assigned altitudes and cruise speeds so that they could be strategically separated. The LOA also required pilots/signatories to automatically change frequency when exiting Class B Airspace (CBA). However, frequency changes to different sectors were not automatic and still required the controller to make sector handoffs. Also, where possible, point-outs were included in the LOA. For example, any UAM flights flying Spine road (the route between East and West complexes at DFW) had point-outs between the DFW East and West Towers.

The final set of scenarios, M1 to M3 in Table 1, referred to as Modified Routes with LOA, used a modified version of the current helicopter routes. These modified routes (see Figure 2) were designed to avoid approach and departure paths for traditional flights, any common Temporary Flight Restrictions (TFRs), heavily populated areas, and more. These modified routes were also assigned altitudes and cruise speeds as per the LOA. For example, in Figure 2 the red, yellow, green, and blue routes set UAM flights at 400, 500, 600, and 1000 ft AGL, respectively. All other elements of the LOA were also in effect for this condition. The modified routes also included new routes that could be used bidirectionally such as the Central Expressway and I-30.

During the simulation, any participant position could deny flights into Class B airspace due to workload concerns. In the operational world, these flights would be worked into the sectors, but in the simulation environment they were removed by the pilot on controllers' command based on their demands and an input regarding the reason for the removal was also made into the system.

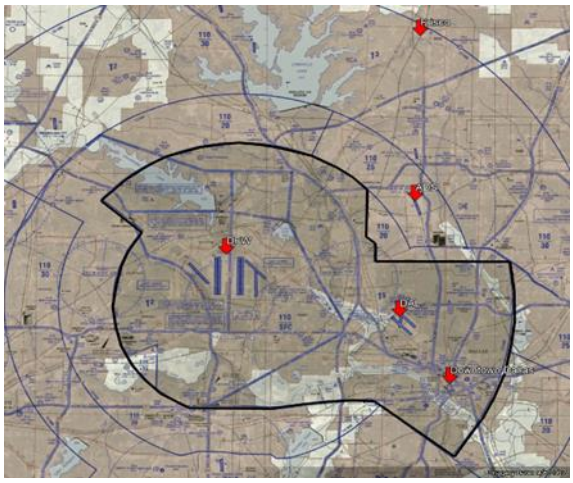

Figure 1. Class B Airpsace in DFW as shown by black boundary, the red arrows show origin destination points and blue routes are helicopter routes

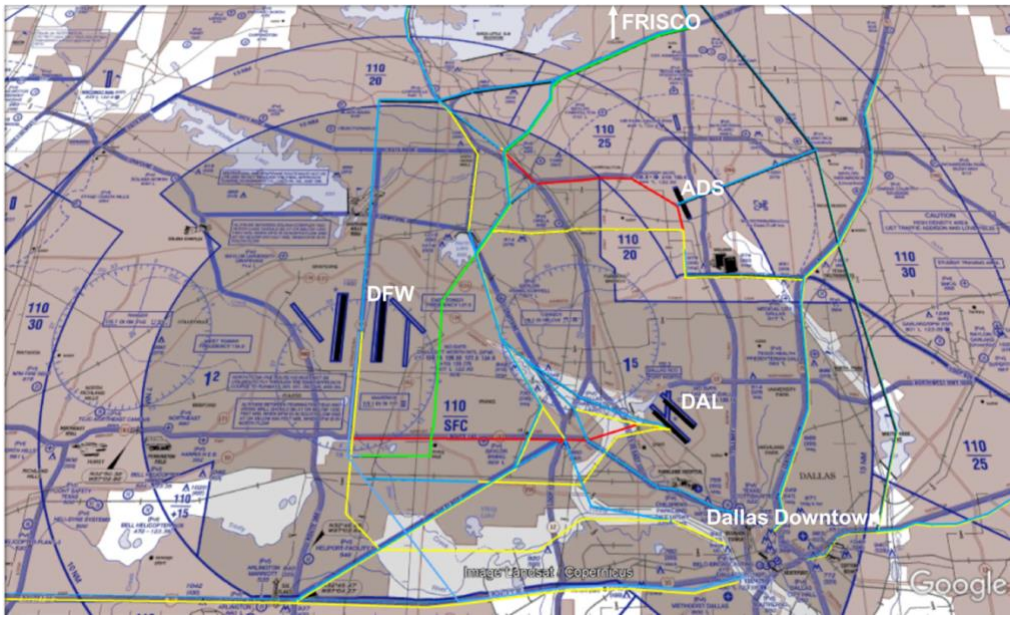

Figure 2. Modified Routes in DFW Area (red routes are at 400ft, yellow routes at 500ft, green at 600ft and Blue routes are at 1000 ft AGL)

B. Test Airspace

The test airspace that was simulated for this research was managed by the DFW East Tower in South flow only. UAM traffic using helicopter routes flew 500 AGL, or 1100 MSL in one direction and 1000 AGL, or 1600 MSL in the other direction. In addition, DAL and ADS airspace were also simulated. DAL is part of Class B airspace, where ADS represents Class D airspace. The initial set of routes investigated in this study were published helicopter routes in the DFW area. Figure 1 shows Class B airspace in the DFW area and the origin/destination city pairs (depicted as red arrows in Figure 1) where UAM flights flew along with helicopter routes shown in blue. For the purpose of the test, helicopter routes spanning the east complex of DFW airport, DAL and ADS were evaluated.

C. Equipment and Facilities

The simulation was conducted at NASA Ames Research Center's Air Traffic Control (ATC) laboratory. This laboratory uses Multi Aircraft Control System (MACS) as its primary software that emulates Standard Terminal Automation Replacement System (STARS) and is used as a rapid prototyping tool for various studies. For this study, the laboratory was configured to represent DFW Tower, DAL Tower and ADS Tower via MACS displays. All the traffic outside the towers were handled by "ghost" confederate positions. The pseudo-pilots and confederates who flew these flights also used MACS in a separate area of the laboratory and communicated over the radio.

D. Participants

Participant positions for this research effort included DFW Tower Local East-3, or DFW LE-3, DAL Helicopter, or DAL Helo position, and ADS Tower controller. Sectors surrounding the positions included DFW Local East-1, DFW Local West, DAL Tower position, and D10 TRACON. These positions were simulated as "ghost" confederate positions. There were a total number of six participants, four were recently retired from the DFW area and two others who were retired from Northern California Terminal Radar Control (TRACON) who staffed the ADS position. All participants rotated between the confederate and participant positions at the start of each new trial. The D10 confederate position was staffed by an in-house controller. All participants completed all experimental conditions in both the confederate and participant positions.

E. Data Collection

Data were collected over five days. The simulations were conducted in blocks starting with Baseline (Current Routes) condition, followed by Current Routes with LOA and Modified Routes with LOA. Each condition had three levels of traffic that were repeated, so every condition ended with six runs and was conducted as a block of runs. Every run lasted about 40 min. Prior to each block condition, the participants spent two to three hours training on the next condition. During the study, MACS' built-in data collection system captured all relevant data, including all aircraft states, trajectories, automation and operator events. All displays were recorded by a commercial screen capture product. At the end of each run, participants responded to a questionnaire that included questions on workload, situational awareness, and acceptability of routes and procedures. At the end of each block of runs and the whole simulation, the participants responded to surveys that focused on the specific condition used for the six-run block and all the conditions at the end of the simulation; respectively. All questionnaires (e.g., post-run, post-block and post-simulation) were administered electronically at the participant position.

IV. Results

The results presented in this paper include desirable trends of UAM aircraft count metrics by each controller position (DFW LE-3, DAL Helo, and ADS), mean lateral separation between UAM flights by position, controller workload, and qualitative feedback on routes, procedures and communications. Descriptive statistics are described in this section, no inferential statistics were conducted due to small number of participants. For detailed descriptions of Workload and Situational awareness and other subjective feedback, the reader is referred to another paper [12].

A. UAM Aircraft Count

UAM Aircraft count is described using three metrics, the average UAM aircraft count, average number of UAM flights that were removed by the controller when they denied access to Class B airspace, and the percentage of flights that were managed by the controller as compared to what was planned for the sector for the simulation run, this number was reduced due to the removal of flights. The amount of traditional traffic managed by all the positions was the same across all the runs as shown in Table 3.

The metric related to average aircraft count refers to average number of UAM flights managed at any given time by a position. The average numbers of UAM flights every second were calculated and averaged over 5 min intervals as well as one average across the entire 40 min run.

1. DFW Local East 3 Controller

Figure 3 shows the average total UAM aircraft that were managed by the DFW Local East-3 position at any given time for the three conditions. The DFW LE-3 position is primarily responsible for arrivals into Runway 17L. In addition, they managed UAM flights arriving from Frisco to DFW, and also managed departures from DFW into DAL

as well as departures to ADS. The total number of UAM flights managed by this position, in the low traffic condition was approximately seven aircraft across the three conditions shown on x-axis. In the medium level traffic, the total average increased from Baseline condition (*M*=9.6, *SD*=3.1) to Current Routes with LOA (*M*=10.8, *SD* =3.5) and stayed about the same for the Modified Routes (*M*=10.4, *SD*= 3.1) relative to Current routes with LOA condition. In the high traffic levels, average number of flights increased from Baseline condition (*M* = 10.6, *SD* = 2.8) to Current Routes with LOA condition (*M* = 15.0, *SD* = 4.8) and stayed about the same for the Modified Route condition (*M* = 15.4, *SD* = 4.4) relative to Current routes with LOA condition. The following trends were observed: the number of UAM aircraft managed by the DFW LE3 position increased as traffic levels increased from low to high. There was an increase in number of UAM flights that were managed due to modification of routes and procedures. It was also observed that LOA seems to have a bigger impact on the number of UAM flights that were managed, than modification of routes. For example, in the high traffic condition, number of UAM flights managed changed from 10 in Baseline condition to 15 in Current Routes with LOA, but stayed about the same for Modified Routes with LOA condition relative to Current Routes with LOA condition.

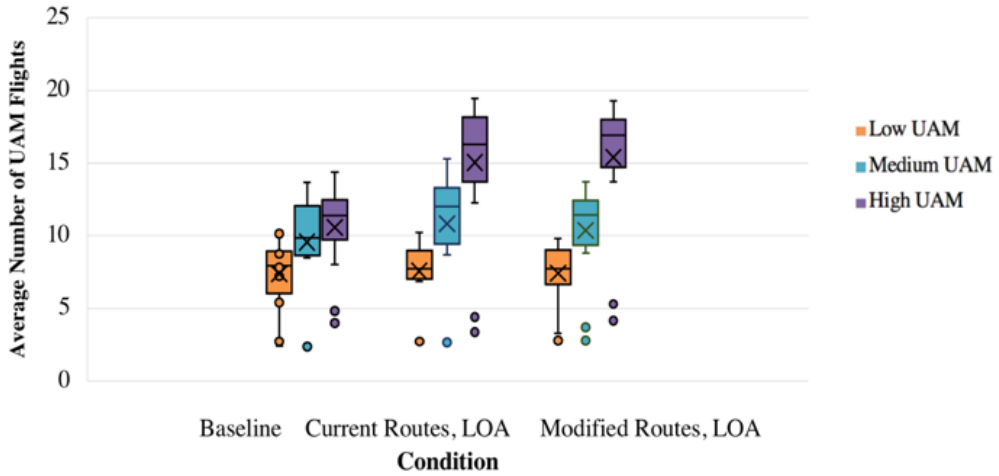

Figure 3. Average number of UAM managed DFW LE-3 controllers at any given time, the circles show the data points

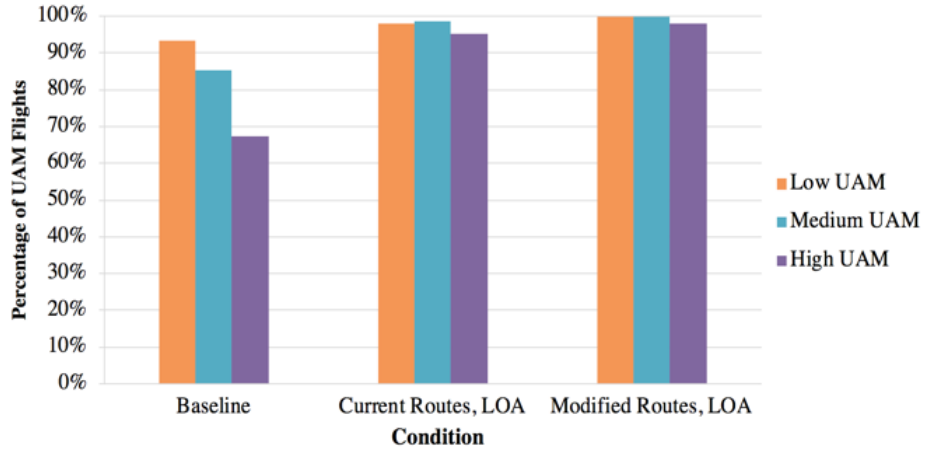

Figure 4. Percentage of UAM flights managed of those planned for DFW LE-3 position

Figure 4 takes into consideration the number of flights that were removed by the DFW LE-3 position. Any participant position could deny flights into Class B airspace. It was found that the highest number of flights that were removed was 32 flights in the Baseline under High traffic condition, whereas only five flights were removed in the Current routes with LOA under High traffic condition, and only two flights were removed in the Modified Routes

with LOA under High traffic condition. This does indicate that the modification of routes and procedures led to the removal of fewer flights and this had an impact on the percentage of UAM flights that the controller managed during the 40 minute long run as shown in Figure 4. This percentage was lowest for the Baseline condition. For example in the Baseline and High traffic condition, approximately 67.5% of flights were managed. However, in the Current with LOA and Modified conditions with high traffic, the controllers managed almost 100% of the UAM flights planned for these runs. As mentioned earlier, the LOA was intended to reduce communication load on the controller and allow handling of more UAM flights than the Baseline condition without LOA, which uses current day communications due to absence of LOA.

2. DAL Helicopter (Helo) Position

A similar analysis of the average number of UAM aircraft managed by the DAL Helo position controller, the average number of UAM flights removed, and percentage of flights managed are described in this section. DAL Helo position was responsible for helicopter traffic in and around DAL and Dallas Downtown, all of which were positively controlled since they fall in Class B airspace. In this HITL study, UAM flights into and out of the DAL airport, as well as into and out of Downtown Dallas were managed by DAL Helo position. There are several helicopter routes that merge at Downtown Dallas (see Figure 2). In the conditions where LOA was assumed, the area around Downtown Dallas was created as a non-movement area, and the UAM flights contacted DAL Helo position when they reached one of the transition points defined in the non-movement area. The rationale for creating the non-movement area was to allow UAM flights to move between vertiports inside the downtown area without getting approval from the tower controller, thus reducing communication workload on the controller. Figure 5 shows box and whisker plots for the average number of UAM flights that were handled by this position at any given time. We see a similar trend for DFW LE-3 in Figure 6, where in general, there is an increase in UAM traffic managed by the DAL Helo controllers as traffic level increases, except in the Baseline condition. We also see a general increase in the UAM traffic managed across conditions. For example, under the high traffic condition, there is a trend for increase in the average UAM traffic managed across conditions - Baseline condition (M = 6.0, SD = 1.9), Current routes with LOA (M = 9.1, SD = 3.5), Modified Routes with LOA (M = 11.5, SD = 3.1). The DAL Helo position was able manage the highest level of traffic, approximately 15 UAM flights, under Modified Routes with LOA.

The highest number of UAM flights that were removed from DAL Helo was in the Baseline condition. As many as 44 flights were removed from the DAL Helo's sector in the Baseline under High traffic condition, which decreased to about 34 flights in the Current Routes with LOA under High traffic condition and further decreased to 12 in the Modified Routes High traffic condition. Figure 6 illustrates the percentage of flights that were managed by the DAL Helo position. This position managed fewer flights in the Baseline condition, especially under high traffic (42%), which improved in the Current Routes with LOA condition under high traffic (65%). Almost 90% of the UAM traffic was managed under the Modified Routes with LOA conditions as planned, irrespective of the UAM traffic levels. The big improvement in percentage of traffic managed under the Modified Routes conditions was possible due to the elimination of some unusable, original helicopter routes such as Tollway and I-35 that created conflicts with approaches into DAL and departures from both DAL and ADS.

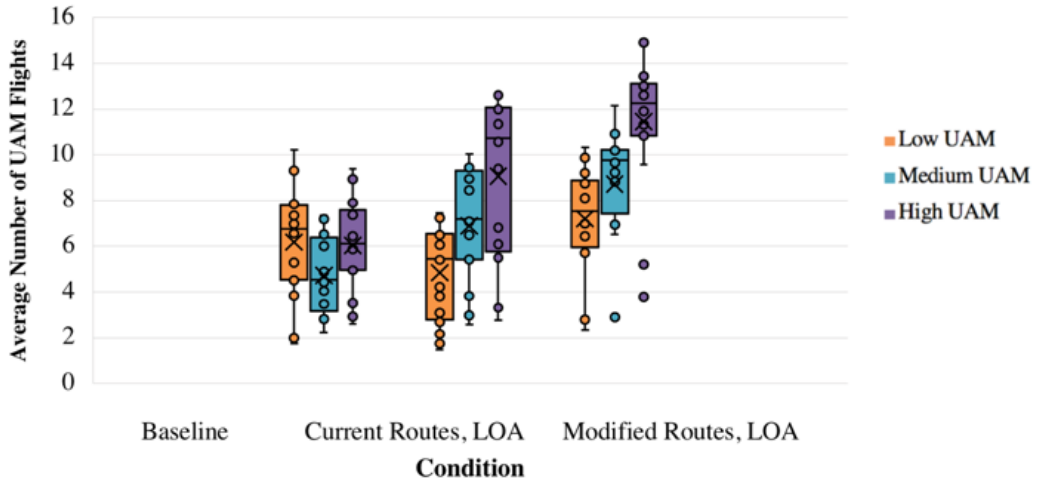

Figure 5. Average number of UAM flights managed by DAL Helicopter controllers at any given time, the circles show the data points

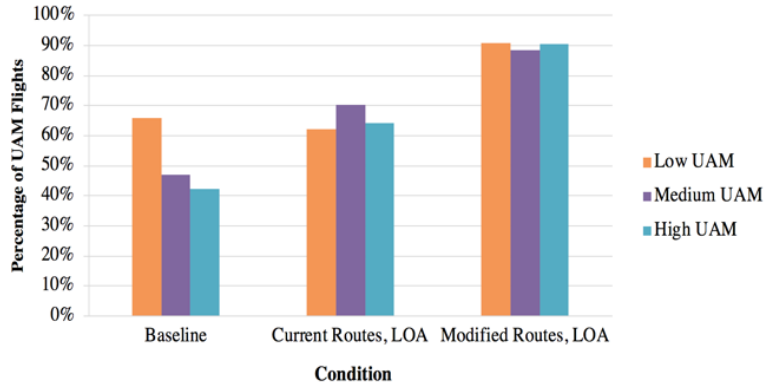

Figure 6. Percentage of UAM flights managed of those planned for DAL Helo position

3. Addison Tower Position

A similar analysis of average number of UAM aircraft managed by the controller, the average number of UAM flights removed, and percentage of flights managed by the ADS Tower position are described in this section. ADS Tower is responsible for traffic into ADS airport, which is Class D airspace that mostly manages flights flying under Visual Flight Rules (VFR). In this airspace, it is necessary for the controller to establish a two way communication with the UAM flight or any other flight, but radar identification is not required. Figure 7 shows that on an average this position managed about three UAM flights in addition to their background traffic. The number of UAM flights managed between the Baseline (M = 2.6, SD = 1.8) and Current routes with LOA high traffic level conditions stayed about the same, whereas the Modified Routes with LOA featuring high traffic level saw the average traffic managed by the controller relatively decrease (M = 1.5, SD = 0.6). We see this decrease in traffic because the modification of the routes removed some routes going through ADS. For example, the Tollway was removed as the controllers referred to it as unusable due its close proximity to DAL arrivals and departures as well as ADS departures. It was observed that flights were mostly removed due to unusable routes in Baseline condition, or roughly four flights in the high traffic level, and in the Current Routes with LOA about six flights were unable to use the routes in the high traffic level, whereas no flights were removed in the Modified Routes with LOA conditions irrespective of traffic level. This had an impact on the percentage of flights managed by the controller as compared to flights planned through their sector as shown in Figure 8. The least amount of traffic managed by the controller was 75% for Current Routes with LOA high traffic level condition. The highest amount of traffic managed by ADS tower was 100% traffic planned in all the Modified Routes with LOA conditions, which was less than the other conditions due to the modifications of the routes.

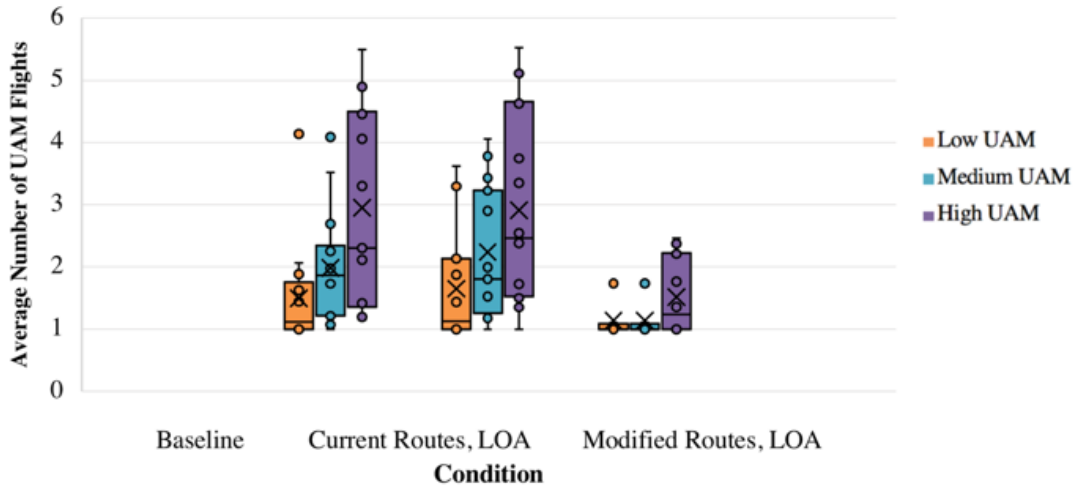

Figure 7. Average number of UAM flights managed at any time by ADS Tower position

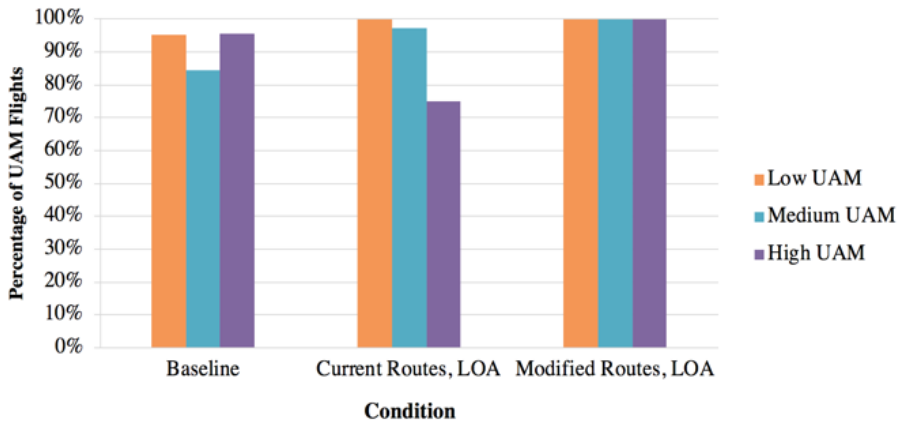

Figure 8. Percentage of UAM flights managed of those planned for ADS Tower position

B. Actual Separation between UAM flights

The actual mean lateral separation between UAM flights that were on the same route and in the same direction was also measured. There is no standard separation requirement for helicopter or UAM flights. For simplicity, only one route was chosen for each position and was investigated across the different conditions. Also, there was not enough traffic in the ADS Tower's sector on any given route that could be compared across conditions. Thus, the two positions analyzed in this section are DFW LE-3 and DAL Helo positions. The route from Frisco to DFW airport is analyzed for the DFW LE-3 controller and the route from Downtown Dallas to McKinney is analyzed for the DAL Helo position. Box and whisker plots as shown in Figure 9 and 10 show the mean actual lateral separation between the flights, the maximum and minimum lateral separation scores, as well as their variability, shown by the whiskers. The dots/ circles represent individual scores.

1. DFW LE-3 controller

Figure 9 shows the average lateral separation between flights on the route from Frisco to DFW, which was managed by DFW LE-3 controllers. Average separation between flights on this route was high between flights in the Baseline with low traffic condition (M = 5.1 nm, SD = 2.3 nm), and was about the same in the low traffic scenarios for Current Routes with LOA condition (M = 4.6 nm, SD = 0.7 nm) and Modified Routes with LOA condition (M = 4.5 nm, SD = 0.6 nm).

With medium traffic levels, the separation was approximately the same across the three conditions -Baseline condition (M = 3.3 nm, SD = 0.6 nm), Current routes with LOA (M = 3.0 nm, SD = 0.7 nm) and Modified Routes with LOA (M = 3.3 nm, SD = 0.6 nm). However, the range of the scores depicted by the size of the box shows that the range of lateral separation on the routes decreases for the Current Routes with LOA condition and stays the same between Current Routes with LOA and Modified Routes with LOA runs. In the heavy traffic condition, the separation maintained by the flights on this route was about two nautical miles across conditions. It was observed that the DFW LE-3 controller tried to handle more UAM traffic in the high traffic conditions than they could provide service to especially in the Baseline condition by not following the full communication protocols. This in turn would explain their smaller spacing between flights in the High Traffic condition.

2. DAL-Helo position

Figure 10 shows the actual mean lateral separation between flights on the Downtown to McKinney route in the DAL Helo's sector. In the Low traffic condition, we see that the flights are able to fly closer and their spacing is reduced from the Baseline (M = 7.4 nm, SD = 4.3 nm) to Current Routes with LOA (M = 5.9 nm, SD = 1.4 nm) and again increases in the Modified Routes with LOA condition (M = 7.4 nm, SD = 4.6 nm) relative to Current Routes with LOA. Under medium traffic, the three conditions have about the same average separation between UAM flights but their variability decreases from the Baseline, (M = 4.4 nm, SD = 1.4 nm), to the Current Routes with LOA (M = 4.6 nm, SD = 0.9 nm) and again increases for the Modified routes with LOA conditions (M = 4.9 nm, SD = 1.8 nm) relative to Baseline condition. Under the High Traffic condition, the mean and variation of separation between the UAM flights are: Baseline (M = 4.0 nm, SD = 1.4 nm), Current routes with LOA (M = 4.17 nm, SD = 1.1 nm), and Modified Routes with LOA condition (M = 3.7 nm, SD = 0.6 nm). It is seen that there is a trend for similar separation

across the three conditions in the High Traffic runs. The trend also shows a slight decrease in variability of the separation, which means that there were no big gaps between most flights on that route especially under the Modified Routes with LOA conditions.

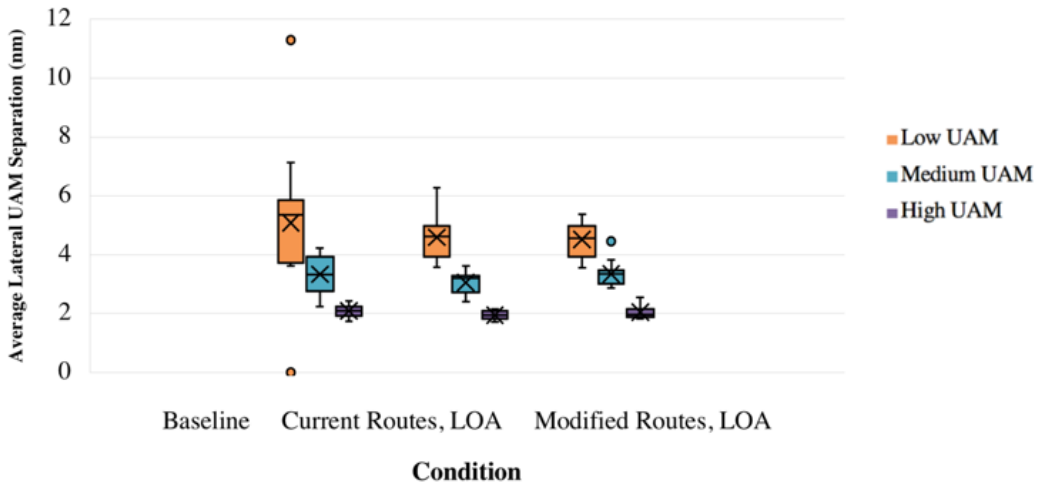

Figure 9. Actual average lateral UAM separation on the route Frisco to DFW managed by DFW LE-3 position, where the dots show data points

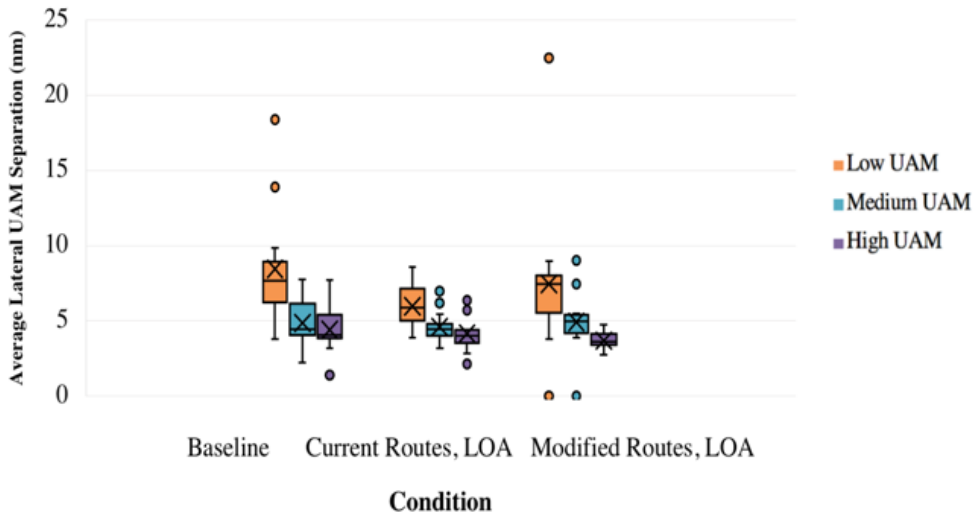

Figure 10. Actual average lateral UAM separation on the route Downtown to Mckinney managed by DAL Helo position

C. Subjective Feedback

During the study, participants were requested to respond to various questions at different points in time: post-run, post-block, and post-simulation. Their responses have been delineated in this section.

1. *Self-Reported Workload*

Workload was measured using several different tools and scales such as the Workload Assessment Keyboard (WAK) and NASA Task Load Index (TLX). These workload metrics have been discussed in a different paper [12]. This section discusses the responses that different controller positions provided at the end of the block of runs pertaining to a condition. They responded to the statement: "My workload level negatively impacted my performance." A score of 1 indicated "strongly disagree" and a score of 7 referred to "strongly agree" on a scale of 1 to 7. The pattern of results is depicted in Figure 11 for different conditions as experienced by all controller positions. There is a trend seen in the responses here, such that the workload perceived under the Baseline condition (M = 4.7, SD = 1.5) was reported as negatively affecting performance (higher workload) when compared to the other conditions Current Routes with LOA (M = 3.8, SD = 1.7) and Modified Routes with LOA (M = 3, SD = 1.7). The Modified Routes with LOA helped the controllers keep their workload under control without severely affecting their performance. Similarly, when asked about whether their workload was operationally acceptable (see Figure 12), participants rated it at about the same level for Baseline condition (M = 4.3, SD = 2.2) and Current Routes with LOA condition (M = 4.3, SD = 1.9), whereas modified routes with LOA (M = 5, SD = 1.7) were considered as more operationally acceptable than other conditions, mostly since there was improved task efficiency and reduced communications. However, Figure 13 shows that for the same question the responses varied by the controller position. The DFW LE-3 position controllers that managed arrivals on runway 17L did not perceive their workload to be operationally acceptable, whereas the controllers positions at smaller airports (DAL and the Class D airport ADS) perceived the workload to be relatively more acceptable possibly due to less volume of operations they handle, compared to what DFW handles for traditional traffic.

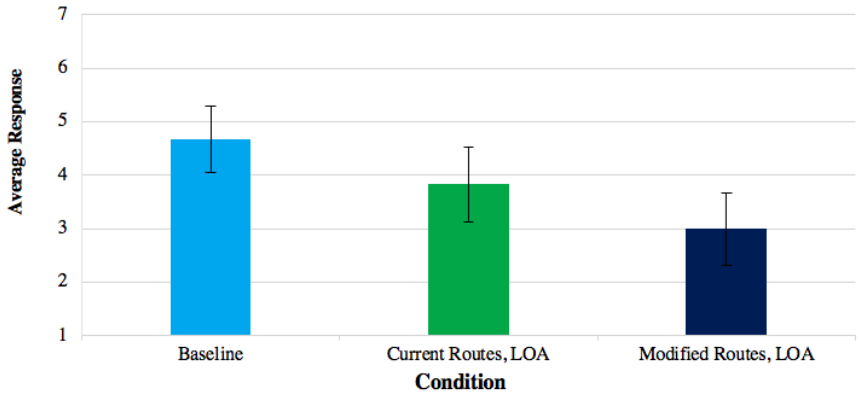

Figure 11. Average responses to "My workload level negatively impacted my performance" (1 = Strongly Disagree and 7 = Strongly Agree) by condition

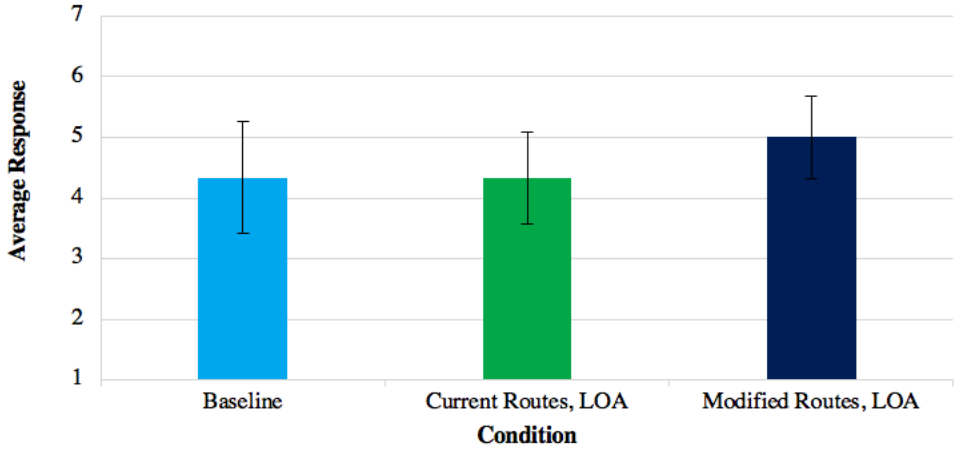

Figure 12. Average responses to "My workload was operationally acceptable" (1 = Strongly Disagree and 7 = Strongly Agree) by condition

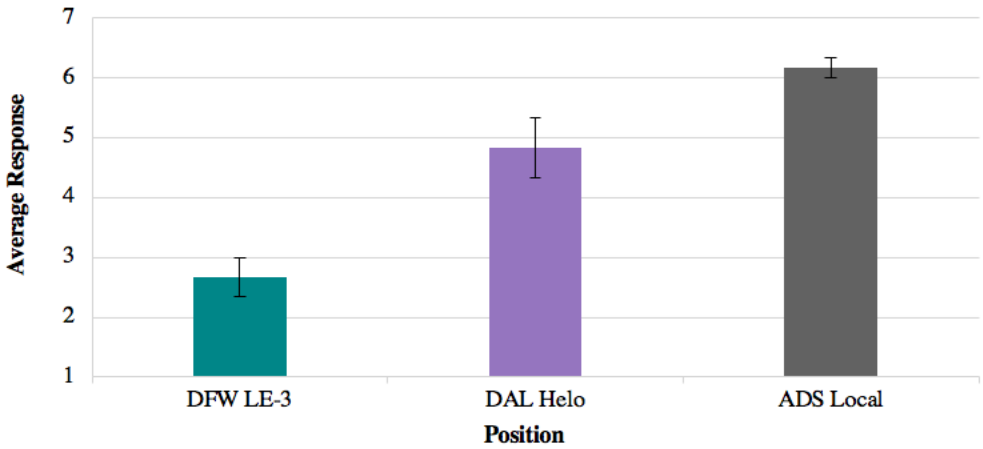

Figure 13. Average responses to "My workload was operationally acceptable" (1 = Strongly Agree and 7 = Strongly Agree) by controller position

2. Communications

Figure 14 illustrates the controller response to the question whether communications were manageable and was asked after a block of runs pertaining to a condition. The participants provided a rating on the Likert scale where a score of 1 was equivalent to "not manageable" and 5 referred to "manageable." The scores were averaged across the three positions. As shown in Figure 14, the controllers reported that communications were at slightly above medium levels of manageability across the conditions. This is an interesting subjective result, when analyzed along with the average number of flights managed by the controllers (previously seen in Figures 3, 5, and 7). We see there was a trend where average aircraft increased as we moved from Baseline to the Modified Routes with LOA conditions when compared to Baseline condition, except for ADS Tower controller. In general, even though the controllers managed higher numbers of UAM flights, they reported the same level of communications manageability across conditions. This can be interpreted such that LOAs helped to keep communications at a relatively similar level while increasing the number of flights that were managed under the Modified Routes with LOA condition.

The subjective feedback provided about communications manageability was supported by an additional metric computed from actual audio transmissions, percentage of time controllers spent with listening to, responding to, and initiating communications with pilots over the radio, as shown in Figure 15. The controllers on average spent almost 55% of their time communicating in Baseline condition. We also see a trend where the introduction of the LOA reduces communications in both the Current with LOA conditions (43%) and Modified with LOA conditions at 46% relative to Baseline condition the time spent communicating, possibly due to increased UAM traffic managed under these conditions.

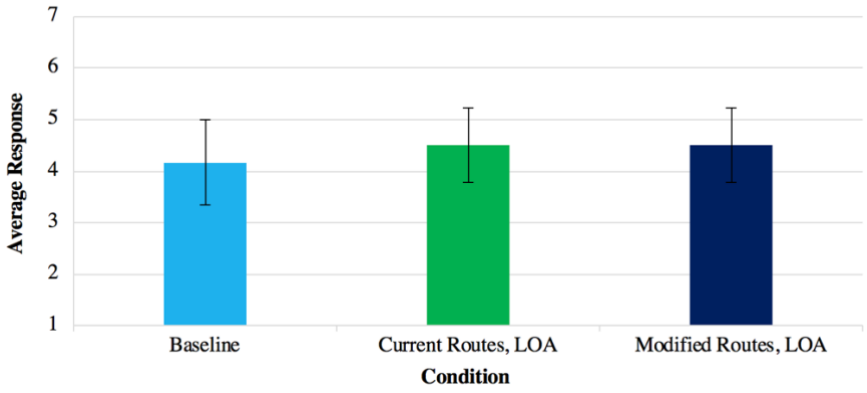

Figure 14. Average responses to "My communications were manageable" (1 = Not Manageable, 5 = Manageable) by condition

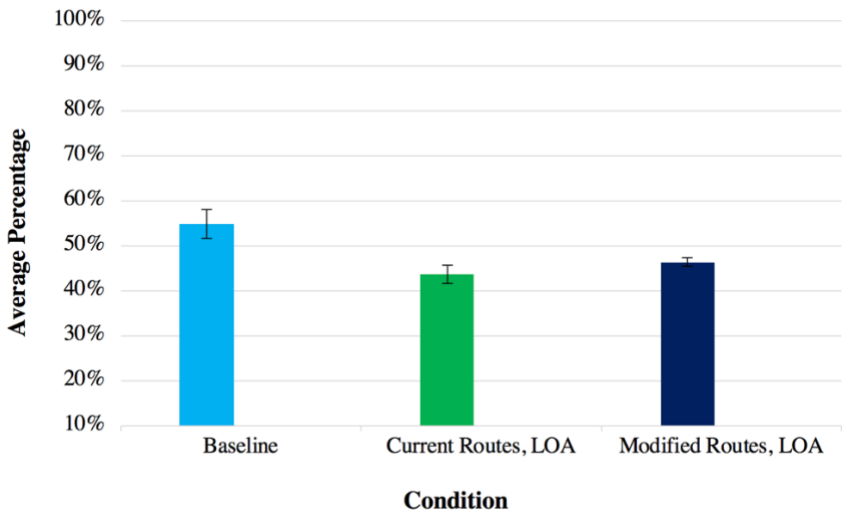

Figure 15. Average percentage of time spent communicating by all controllers by condition

3. Routes and Procedures

Participants were asked to respond to several subjective questions regarding routes and procedures. Some questions were asked during post-run surveys and others were asked during post-block surveys. Figure 16 shows responses to a question on how operationally acceptable the routes were, which was asked after every run. The figure shows that there is a trend for improved acceptability towards Modified Routes with LOA and least acceptability for the Baseline condition, where current day routes and communication procedures were used by the controllers for managing UAM flights. The controllers reported that the current helicopter routes were not ideal for high volume UAM operations.

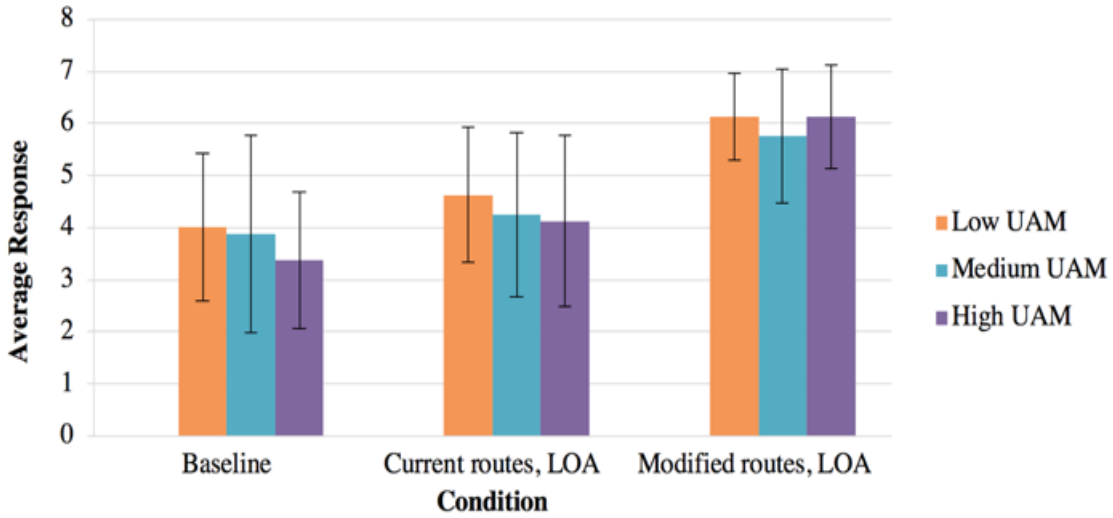

Figure 16. Average responses to "The routes used were operationally acceptable" (1 = Not Acceptable, 7 = Acceptable) by condition

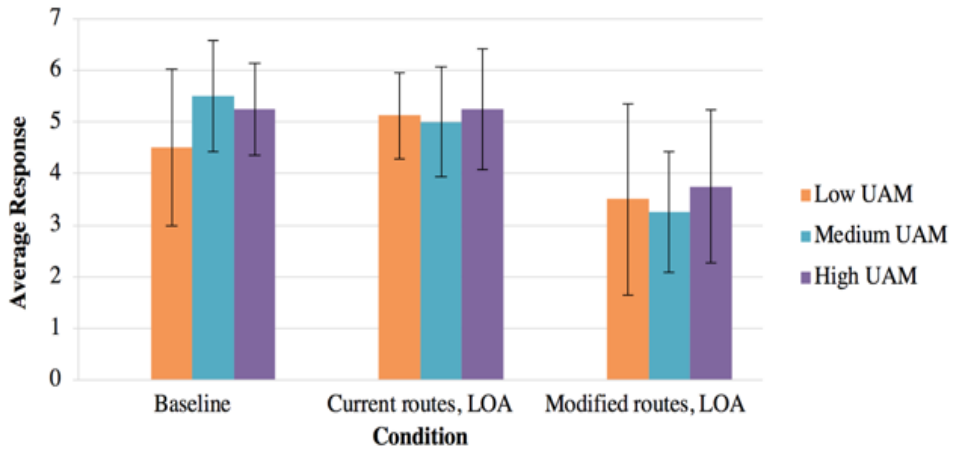

Figure 17. Average responses to "Did UAM routes need improvement?" (1 = Need No Improvement, 7 – Improvement Needed) by condition

Figure 17 shows average responses towards the question regarding whether the routes used during the run require improvement or not. A score of 7 indicated necessary improvement, whereas a score of 1 meant that no improvement was needed. As expected, the controllers reported that lesser improvement was needed for Modified routes with LOA, whereas more improvement was required for the current routes both in the Baseline and the Current Routes with LOA conditions. The current helicopter routes that were used for UAM operations were analyzed by Subject Matter Experts (SMEs) and had several issues, such as proximity to approach and departure paths for traditional traffic that required controller attention and affected their workload.

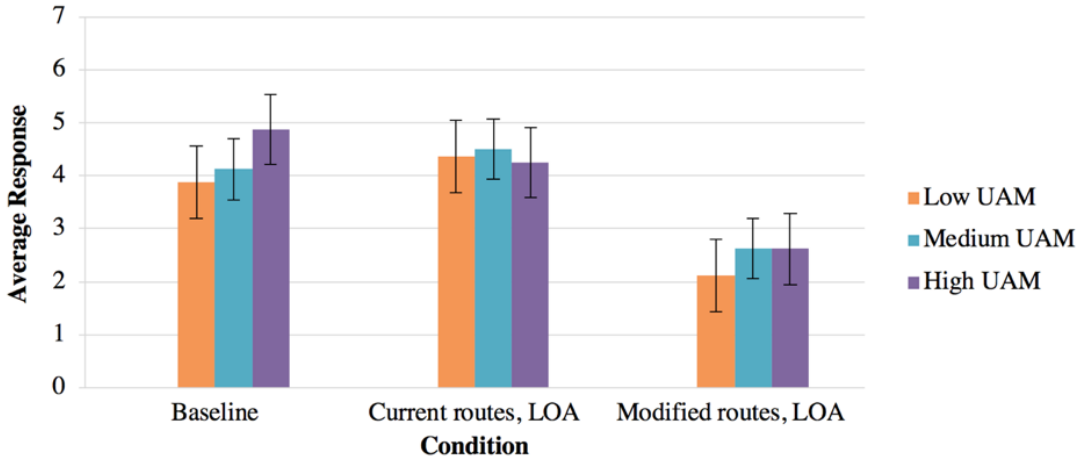

Figure 18. Average responses to "Did UAM routes increase task complexity?" (1= Not Complex, 7 = Complex) by condition

Figure 18 shows whether controllers perceived the UAM routes as increasing task complexity, where a score of 1 indicated that they did not increase task complexity and a score of 7 indicated significant task complexity. There is a trend observed in the data shown in Figure 18, where there is a decrease in task complexity offered for the Modified Routes with LOA condition. Roughly similar levels of task complexity occurred for the conditions that utilized current helicopter routes (the Baseline and the Current Routes with LOA conditions). Most controllers reported that Modified Routes with LOA improved efficiency because the tasks were somewhat simplified with the help of modifications to the original helicopter routes and elimination of some communications via the LOA. Even though the LOA helped the condition, the Current Routes with LOA condition was not able to remove the complexity of routes due to their proximity to traditional traffic and intersecting helicopter routes that required separation, thus increasing communication load on the controllers.

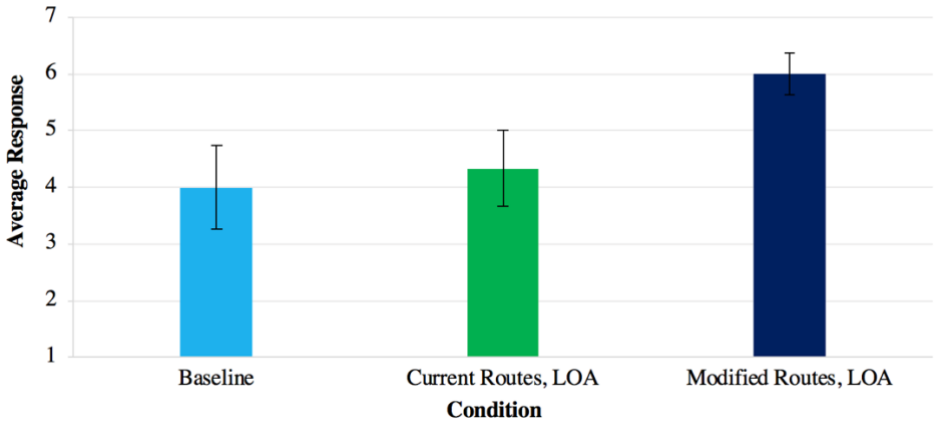

Figure 19. Average responses to "Did UAM routes support efficiency?" (1 = Low, 7 = High) by condition

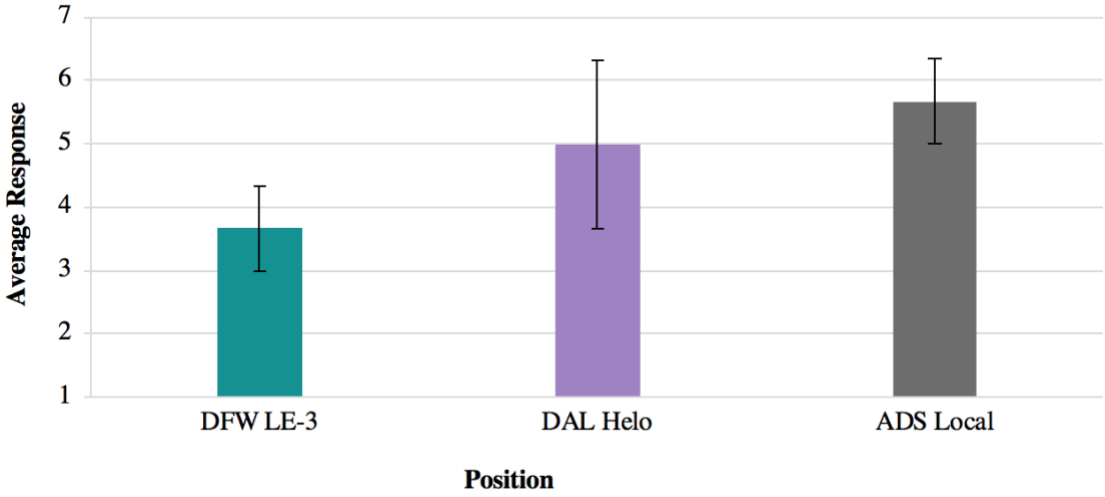

Figure 20. Average responses to "Did UAM routes support efficiency?" (1 = Low, 7 = High) by controller position

Figure 19 and 20 illustrate how UAM routes supported efficiency as perceived by the controllers. The controllers reported their scores on this question during post-block surveys, where a score of 1 referred to low efficiency and 7 referred to high efficiency. The scores were averaged across all the controllers and level of traffic. In Figure 19, we see a trend across the conditions where the participants rated that an improvement of efficiency provided by routes and procedures from the Baseline conditions, to Current Routes with LOA conditions to the Modified Routes with LOA conditions. The controllers reported that the LOA played a big role in separating the traffic on current routes and reducing communication load. The Modified routes with LOA conditions further reduced communication by eliminating the need for traffic calls, since the UAM routes were separated from approach and departures paths. The results on the efficiency provided by the routes is further explored for the different controllers as shown in Figure 20. The DFW LE-3 controller, whose primary responsibility is to manage 17L arrivals, reported that the UAM routes distract from the primary task. Since the UAM routes were in the South of the airport, this addition increased the field of view or scanning area, thus making it hard to pay attention to all the routes. The DAL Helo position participants did comment that the UAM routes were more usable after the modifications and improved efficiency. For example, using Central Highway as a route allowed for greater efficiency than using Tollway, which always required re-routing of UAM traffic to avoid traditional traffic. ADS Local found the routes most usable and efficient. This is most likely

because most of their traffic in Class D airspace is VFR traffic and it did not impact the rest of their traffic except for the Tollway route.

V. Discussion

The experiment reported in this paper investigated routes and procedures for UAM near-term operations, with a focus on investigating operational capabilities and limitations. For the purpose of this research, we started with current airspace constructs such as helicopter routes and current communication procedures for entering Class B and D airspaces. There were two other conditions investigated. The second condition included the current helicopter routes, but reduced communication via a Letter of Agreement (LOA). The third condition was to use modified helicopter routes with LOA that aimed to separate UAM traffic from traditional commercial traffic. It was hypothesized that the modification of the routes and the introduction of the LOA will reduce workload and communications' load. Controllers reported that the LOAs, which assigned route names, pre-assigned beacon codes, and called out point-outs, simplified entry and exit communications procedures for Class B and Class D airspaces, and allowed them to manage more UAM traffic in addition to their primary responsibility of managing traditional traffic. Controllers also mentioned that the introduction of the LOA affected the number of UAM flights that they could manage, which were more flights managed than what the modification of the routes helped achieve. The number of UAM flights that the controller could manage improved from the conditions that used the current routes (e.g., the Baseline and Current Routes with LOA conditions) to the Modified Routes with LOA. A similar result was seen for the percentage of flights managed of those planned for that sector. The Modified Routes with LOA allowed DAL Helo to manage almost 90% of the UAM flights that were planned, versus about 70% managed using Current Routes with LOA condition. This notable improvement was seen due to the fact that there were many unusable routes that were removed in the Modified Route conditions.

The modifications to the routes and procedures allowed DFW LE-3 and ADS to manage all UAM flights to full capacity as planned. The reason DAL Helo position could not handle as many flights using the current helicopter routes was due the fact that there were a couple of routes that were unusable due to their proximity to approach and departure paths of traditional traffic. The separation between flights also decreased between the Baseline conditions and the conditions with LOA. Some effects of social desirability were also seen where the DFW LE-3 controllers attempted to manage more flights in the high traffic scenario than they could especially under the Baseline condition, where they did not follow full communication protocols to the UAM flights as expected.

Controllers reported that workload did not negatively impact their performance under the Modified Routes with LOA condition and found the workload to be operationally acceptable. The controllers at the large airport, or DFW LE-3, did not report that their workload was operationally manageable. During debriefs, they mentioned that the UAM flights and their routes were so widespread, that it took their attention away from their primary task of managing arrivals to the runways. They also mentioned that this task of managing additional UAM flights would be difficult given their current workload. Feedback regarding communications showed that controllers spent almost 50% of their time communicating with UAM flights and traditional commercial traffic in the Baseline condition. The amount of time spent on communication was reduced due to the introduction of the LOA, which was possibly the reason why the controllers mentioned that the communications were manageable across all the conditions. The LOA is a great tool available for reducing communications, but cannot completely eliminate communication load for controllers. Scalability of UAM operations will be hard to achieve if operations are limited to voice communications between the controller and the flight deck. The participants of the study found the modifications to the current routes and introduction of LOA reduce task complexity and improved efficiency. The modified routes were better separated from traditional traffic and help reduce workload. Thus, the modified routes did outperform the current routes on the various metrics and were considered by different stakeholders to be the direction that the UAM routes could take in the future.

VI. Conclusion

In this research, we considered the guidelines provided for UAM operations [3] to the extent possible. In order to avoid the requirement for additional ATC infrastructure, this research started with current helicopter routes and LOAs that have precedence in the National Airspace (NAS). Also, the authors did not pose any restrictions on traditional airspace users, the modifications were suggested for helicopter routes and not other commercial traffic's approach or departure paths. The research was planned to explore scalability and workload impacts when designing the routes and LOA. However, more considerations may need to be given to safety thresholds and allowing flexibility in the operations.

It was found that current day helicopter routes and communication procedures can support near-term UAM operations, but may not be scalable. Controller workload managing traffic at large airports like DFW is already high enough that we need to re-think roles and responsibilities of air traffic controllers, operators of UAM flights, and the flight deck. In the study utilizing the letter of agreement did accomplish its purpose of reducing communications for UAM flights, but use of voice communications still remains a big factor in controller workload as well as scalability of UAM operations. Future work will explore how UTM paradigm used for managing sUAS will work for UAM operations. The service oriented architecture offered by the UTM paradigm has the potential to be very lucrative. However, more investigation is required for using this paradigm for UAM operations that are likely to occur above 500 ft AGL and pose a greater risk than smaller drones that do not carry passengers.

Acknowledgments

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References

[1] Geister, G. & Korn, B. (2018). Density based management Concept for Urban Air Traffic. Digital Avionics System Conference, London, Sept 2018

[2] Kopardekar, P., Rios, J., Prevot, T., Johnson, M., Jung, J., and Robinson, J. E., "UAS Traffic Management (UTM) Concept of Operations to Safely Enable Low Altitude Flight Operations," 16th AIAA Aviation Technology, Integration, and Operations Conference, AIAA AVIATION Forum, AIAA 2016-3292, Jun. 2016. doi: 10.2514/6.2016-3292

[3] Mueller, E.; Kopardekar, P. & Goodrich, K. (2017). Enabling Airspace Integration for High-Density On-Demand Mobility Operations. 17th AIAA Aviation Technology, Integration, and Operations Conference. 5-9 June 2017, Denver, Colorado. AIAA 2017-3086

[4] Uber Elevate, "Fast-Forwarding to a Future of On-Demand Urban Air Transportation," 2017, https://www.uber.com/elevate.pdf.

[5] Thipphavong, D.P. et.al. (2018) Urban Air Mobility Airspace Integration Concepts and Considerations. 18th AIAA Aviation Technology, Integration, and Operations Conference. 25th-29th June 2018, Atlanta, Georgia.

[6] UAM Market Study - Technical Outbrief (2018). Booz Allen Hamilton. October 2018

[7] Bosson, C. & Lauderdale, T. (2018). Simulation Evaluations of an Autonomous Urban Air Mobility Network Management and Separation Service. 18th AIAA Aviation Technology, Integration, and Operations Conference. 25th-29th June 2018, Atlanta, Georgia.

[8] Kleinbekman, I.C.; Mitici, M. A. & Wei, P. (2018). eVTOL Arrival Sequencing and Scheduling for On-Demand Urban Air Mobility. Digital Avionics System Conference, London, Sept 2018.

[9] Garrow, L. A.; German, B.; Mokhtarian, P.; Daskilewicz, M.; Douthat, T.H. & Binder, R. (2018) If you Fly it, Will Commuters Come? A Survey to Model Demand for eVTOL URBAN Air Trips. AIAA Paper 2018-2882, June 2018

[10] Rios, J., Mulfinger, D., Homola, J., Venkatesan, P., "NASA UAS Traffic Management National Campaign-Operations Across Six UAS Test Sites," IEEE-DASC 2016, Sep. 2016. doi: 10.1109/DASC.2016.7778080 [22]

[11] Aweiss, A. S., Owens, B. D., Rios, J. L., Homola, J., Mohlenbrink, C. P., "Unmanned Aircraft Systems (UAS) Traffic Management (UTM) National Campaign II", 2018 AIAA Information Systems-AIAA Infotech @ Aerospace, AIAA SciTech Forum, AIAA 2018-1727, Jan. 2018. doi: 10.2514/6.2018-1727 [23] Federal Highway Administration,

[12] Edwards, T., Verma, S., Keeler, J. Exploring human factors issues for urban air mobility operations (In Press). AIAA: Aviation, June 17-21, Texas USA.