Exploring Human Factors Issues for Urban Air Mobility Operations

Tamsyn Edwards[1]
San Jose State University at NASA Ames Research Center, Moffett Field, CA, 94035

and

Savita Verma[2]
NASA Ames Research Center, Moffett Field, CA, 94035

and

Jillian Keeler[3]
NASA Ames Research Center, Moffett Field, CA, 94035

Urban air mobility (UAM) is receiving increased attention in aviation as a system for passenger and cargo-carrying new entrants in urban airspace. In order to develop a safe and efficient system, numerous possible concepts of operation for UAM are being explored throughout industry and research domains, the features and assumptions of which may differ according to near, medium and far term operations. Much of the current research into the development of UAM has dominantly focused on technological and engineering capabilities, such as vehicle development. Although these areas of research are essential to furthering UAM, research into the role of the human operator in UAM is limited. The research described in this paper aims to begin to address this gap by investigating the capabilities and implications of human operators as traffic managers in the UAM system, focusing on near-term UAM operations. A human in the loop air traffic control simulation was used to investigate the effect of UAM traffic density, airspace routes and communication procedures on subjective workload and efficiency-related task performance. Findings indicate that medium and high-density operations were associated with high workload. A reduction in verbal communications through a letter of agreement, and optimized routes, were associated with reduced workload and increased performance efficiency. However, even with these adjustments, reported workload remained high, particularly during the high-density scenario. Future research should focus on the human operator roles and responsibilities, and the amount of involvement, in UAM system management. Particular focus should be directed on the impact of reduced human operator involvement and increased automation, on the safety and efficiency of UAM operations and the integration of UAM with traditional air traffic management.

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[1] Senior Research Associate, Human Systems Integration Division, NASA Ames Research Center, Mail Stop 262-4, Moffett Field, CA 94043, AIAA Senior Member.
[2]Senior Researcher, Aerospace High Density Operations Branch, NASA Ames Research Center, Mail Stop 210-4, Moffett Field, CA 94043.
[3]Researcher, Human Systems Integration Division, NASA Ames Research Center, Mail Stop 262-4, Moffett Field, CA 94043.

I. Introduction

Urban air mobility (UAM) is receiving increased attention in the aviation literature as a traffic management system for the operation of passenger and cargo-carrying new entrants in urban airspace [1, 2]. UAM has been defined by the National Aeronautics and Space Administration (NASA) ATM-X project as "a safe and efficient system for air passenger and cargo transportation within an urban area" [3, p.3366). Technological advancements, in combination with falling costs and ride-share business models [2], have facilitated the exploration of UAM as a feasible solution to transporting people and goods around metropolitan areas at greater speed and efficiency [4]. Initial concepts include passenger-carrying vehicles [3]. It is envisaged that passenger transport would be focused on high-density metropolitan areas and rely on fleets of small vehicles carrying 2-6 passengers, focusing on short-distance flights [2, 3].

Although the introduction of UAM offers the potential for significant benefits, such as increased efficiency for customers [4], it also creates the potential for fundamental change to the current air traffic management system. It has been acknowledged in the literature that in addition to technical challenges, including those associated with UAM vehicles such as ride quality and energy efficiency, barriers to the integration of UAM operations in the existing airspace must be considered and mitigated [e.g. 3] to enable safe and efficient integration with the current system. Documented challenges include modifications to the airspace, [4] airspace allocation, demand on human operators, and interactions with traditional airspace users (such as general aviation and commercial aircraft) [5].

In order to facilitate concept development for the safe and efficient integration of UAM vehicles and operations into the National Air Space, NASA will "develop detailed concepts of operations for UAM airspace integration at different stages of operational maturity" [1, p3678]. Phase 1 proposes development of a concept of operations for near term operations. Several assumptions are made in this near-term stage. For example, it is assumed that UAM vehicles will be low-density, and will be restricted to a small set of fixed routes that primarily focus on the current-day helicopter routes around metropolitan areas [1]. In addition, at least for the near term, UAM vehicles are envisaged to be subject to the existing regulations of air traffic. One of the implications of this is that UAM vehicles will be expected to abide by the regulations regarding clearances into controlled airspace (Class A – E) [1]. Specifically, these regulations state that UAM flights would be required to communicate with air traffic control (ATC) prior to entering Class B, C, or D airspace [3] (Class A airspace starts at 18000 feet above mean sea level, which is outside of the intended airspace for UAM traffic) as well as gain a flight clearance prior to take-off within controlled airspace. As a result, this assumption creates an implication for the current ATC system and importantly, air traffic controller (ATCO) workload.

The roles and responsibilities of ATCOs and other human operators in relation to UAM traffic management remain undefined. Concepts need to explore the degree of involvement of human operators, the functions, tasks, and responsibilities of human operators (if any), and the personnel who will fulfill identified functions. Exploration of the human operator role in UAM is therefore an essential element of the progression of UAM concept development. Identifying and exploring human factors issues such as task demand, associated workload, and performance, during an early stage of concept development, affords the opportunity to identify capabilities, as well as potential risks and associated mitigations, of human operator roles.

The research reported in this paper aimed to contribute further understanding of human factors considerations and human operator roles for near-term UAM operations. Specifically, this research aimed to investigate the association between UAM traffic demand, subjective reported workload and efficiency related performance. In addition, the research aimed to investigate the effect of route changes, optimized for UAM traffic, and the introduction of reduced verbal clearances to UAM traffic in association with workload and ATCO efficiency-related performance. To address these aims, a human in the loop simulation was conducted with operational Tower-based controllers from the Dallas areas, including Dallas Fort Worth, Dallas Love Field and Addison Towers, utilizing the Dallas metropolitan downtown airspace for simulation scenarios. The Dallas metroplex area, and specifically, the routes between DFW, Frisco, and downtown, were selected as scenarios to evaluate UAM traffic and ATCO interaction specifically because this area is a desirable near-term applicable of UAM services. Road-based congestion, as well as multiple points of interest within a short distance, create potential customer demand for sky-taxi services. The research was conducted as part of the NASA ATM-X project, and applied Phase 1 assumptions for near-term operations outlined in previous papers [1, 3]. As the nature of the role of the human in near-term UAM traffic operations is still being explored, ATCOs were utilized as participants to explore the effects of UAM traffic and procedures on workload and performance. UAM operations will interact heavily with traditional airspace such as the Dallas metroplex area, and as such, interactions with ATCOs will occur in the near to mid-term future operations. Away from congested airspace (such as near Frisco) more automated UAM operations are expected, in which the interactions with ATCOs might be abstracted to be a more general human-machine interaction paradigm.

Findings have implications for contributing to foundational understanding of human factor considerations and human operator roles in UAM traffic management, which may guide the direction of future research and contribute to informing UAM concept and system design in order to maximize safety and efficiency.

II. Method

A. Design Overview
A human in the loop simulation was conducted to investigate the effect of UAM traffic demand, optimized routes and communication procedures on self-reported controller workload and efficiency-related performance. The simulation was centered on low-altitude tower control sectors in the North Texas Metroplex area. The study used a mixed measures design. Control position served as the between-measures independent variable and consisted of three levels; Dallas Fort Worth (DFW) Local East 3 position (south flow), Dallas Love Field (DAL) helicopter ('helo') position, and Addison tower (ADS) local position.

Three within-measures variables were utilized. Task demand was manipulated to create three simulation scenarios, consisting of *low, medium* and *high* density UAM traffic. Two forms of communication procedure were utilized as the second variable, specifically, *current day* communication procedures and *reduced verbal* communications procedure implemented via a letter- of-agreement (LOA). Finally, the routes available to UAM traffic were manipulated. They consisted of two levels – the use of *current day helicopter routes* and *modified routes* that were optimized for UAM vehicles.

The study did not use a full-factorial design. A total of 9 conditions were completed by each control position. Participants were six recently-retired controllers who had previously worked in tower control. Two controllers participated per control position. Self-reported workload was measured throughout each simulation at 4-minute intervals. Efficiency-related performance was inferred from the number of UAM vehicles controlled in each simulation and percentage of total UAM vehicles that were accepted into controlled airspace. Pseudo-pilots were paired with controllers and completed standard pilot tasks such as controlling the aircraft in accordance with controller instructions and communicating with controllers. Each simulation session lasted for 40 minutes.

B. Airspace
Participants were asked to control airspace surrounding three airports located in the North Dallas, TX, metroplex area. This airspace was observed to be a particularly complex sector given the mix of traffic transiting airspace and the coordination between the three control towers. Specially, participants controlled low altitude sectors from the East local 3 position at Dallas Fort Worth International Airport (DFW) Dallas Love Field, and Addison tower (Fig.1 and Fig. 2).

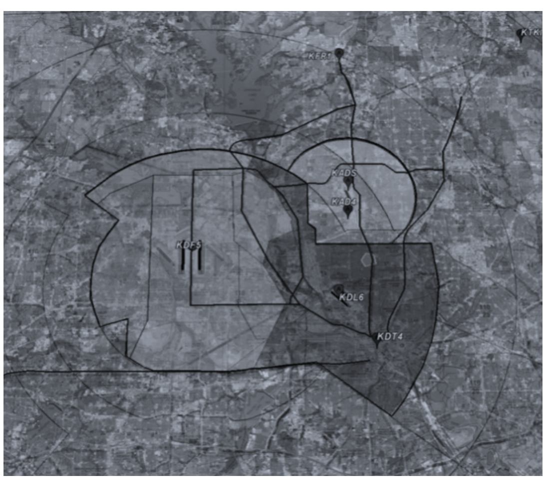

Fig. 1 Sectors and current day helicopter routes used by UAM vehicles

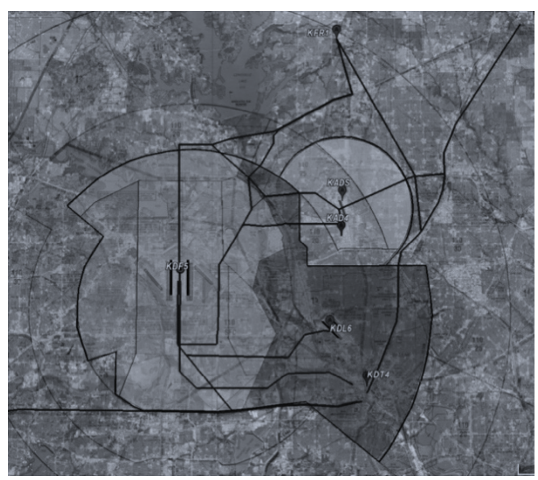

Fig. 2 Sectors and optimized routes for UAM vehicles

C. Experimental Conditions

1. Between-Measures Variable: Controller Position

This study utilized one between-measures variable, and three within-measures variables in order to investigate the effect of UAM traffic demand, optimized routes and communication procedures on self-reported controller workload and efficiency-related performance. All control positions were required to complete a set of tasks in relation to controlling UAM traffic which are described in detail in section C.3. Two participants were assigned work each controller position.

2. Within-Measures Variable: UAM Traffic Density

UAM traffic density was manipulated in order to change taskload. Density was manipulated by increasing UAM traffic count, reducing the spacing distance and time between each UAM aircraft. Three levels of traffic density created, generating three different experimental scenarios, defined in Table 1.

Table 1 UAM traffic density metrics for each simulation scenario

Scenario	Temporal spacing (seconds)	Distance spacing (miles)	UAM Count
Scenario 1: Low UAM density	90	3.75	115
Scenario 2: Medium UAM density	60	2.5	167
Scenario 3: High UAM density	45	1.88	225

Background traffic, specifically, simulations of aircraft using visual flight rules (VFR) and commercial aircraft using instrument flight rules, were included in each scenario based on current day traffic levels and were controlled by participants. Background traffic numbers remained constant across scenarios for each controller positions.

3. Within Measures Variable – Communication Procedures

Two sets of communication procedures were used in this study. The first replicated current day communication procedures for entering/exiting controlled airspace and taking off and landing at airports within controlled airspace. This condition assumed no letter of agreement, or reduced communication requirements, between UAM companies and control facilities and no information broadcast from Automatic terminal information service (ATIS). Controllers were required to perform tasks which were representative of current day tasks for VFR traffic. Tasks included assigning beacon codes, assigning altitude and speed, making traffic calls to both commercial and UAM traffic as necessary, issuing advisories for takeoff and clearance to enter Class B airspace (e.g. *"UAM942, Love Tower, cleared to enter class bravo. Squawk 4043 [additional instructions]")* traffic hand-offs to other sectors and receiving traffic handoffs. Controllers were able to approve requests and issue a clearance, or could choose to refuse entry by stating "unable". The second set of communication procedures simulated a letter of agreement (LOA) between UAM companies and Dallas control facilities. LOAs help reduce the number of verbal elements required, and therefore, time spent on verbal communications. The LOA was used to create standardized routes for UAMs depending on departure point and route. Each route used pre-assigned information such as beacon codes, altitudes and speeds, so that controllers did not need to pass this information verbally, unlike the current day communication procedure. ATIS was used to broadcast UAM traffic locations. Clearances into Class B airspace shorted to only include route names, removing speed, altitude and beacon code elements (e.g. *"UAM173, Love Tower, cleared via [route name]").* Departure advisories were also shortened to only include route information (e.g. *"UAM123 [Airport] Tower, cleared via [route name]"*). Again, controllers were able to approve requests for departure, landing and entry to Class B airspace, or could choose to refuse entry by stating "unable". For further clarity on the differences between 'current day communication procedures' and 'LOA communication procedures', Table 2 presents a full comparison of the differences between communication sets used in the simulation.

Table 2 Differences between communication sets used in the simulation

Communication elements	Current day communication procedures	Communication procedures with LOA
Routes	Current Helo routes, controller assigns altitudes	Current Helo routes with transition waypoints and altitudes defined in LOA
Beacon code assignment	Verbally communicated by controller	Pre assigned via LOA
Route Clearance	Pilot requests full route clearance by describing the intended route	Pilots request route using route name defined in LOA
Class B Airspace Clearance	Explicit clearance is required	Implicit in route clearance
Handoffs (HO)	Manual Handoff for flights going out of sector with usual communication Communication: "leaving CBA, squawk VFR"	No communication for exiting Class B airspace (CBA) Communication required for sectors Handoff
Frequency change	Freq change required to exit Class B airspace and between sectors	Automatic frequency change when exiting CBA, but approval required for sector frequency change within CBA
Point Outs	Point outs are required where necessary	Point outs not required for DFW since they were spelled out in the LOA
Traffic Calls	Controllers responsible for separation in Class B airspace, will make traffic calls as necessary	Controllers responsible for separation in Class B airspace, will make traffic calls as necessary ATIS broadcasts UAM traffic on spine road will alleviate traffic calls under normal conditions

4. Within Measures Variable – UAM Routes

The final variable was the routes available to the UAM traffic. Two sets of routes were used. The first set of routes simulated current day routes used by helicopters (Fig. 1). The second set of routes were a modified version of the current day helicopter routes, optimized for UAM traffic (Fig. 2). Modified routes were designed to avoid approach and departure paths for commercial or VFR aircraft, common temporary flight restrictions and heavily populated areas. In addition, the routes were redesigned to be more direct, and therefore shortened, between departure and landing points. to take account of the limited battery power of electric vertical takeoff and landing (eVTOL) aircraft. The modified routes also included new two-way routes (e.g. Central and I-30).

5. Summary of Experimental Conditions

The three within-measures variables were combined in a non-factorial design to create a total of nine conditions. A baseline condition with no UAM traffic was also created but will not be reported in this paper.
Each controller position experienced all conditions. The conditions are summarized as follows:

- *Conditions 1-3* involved current-day routes and current-day communication procedures (referred to as condition 'C') paired with three different UAM density scenarios. C1 refers to the current day routes and communication procedures, with low density UAM traffic. C2 used the same routes and procedures, but with medium density UAM traffic. Finally, C3 used the same current-day routes and procedures, in association with high density UAM traffic.
- *Conditions 4-6* used current-day routes, but this time, utilized reduced verbal communications via a LOA (referred to as condition 'CL' - Current day routes with Letter of Agreement). Again, the condition was repeated in association with the low, medium and high UAM traffic density scenarios, creating conditions which were labelled CL1, CL2, CL3.
- *Conditions 7-9* used Modified routes (referred to as condition 'M') also with reduced verbal communications via a LOA. The condition was repeated in association with the low, medium and high UAM traffic density scenarios, creating conditions, referred to throughout this paper as M1, M2, M3.

D. Measures
The study reported in this paper is part of a larger study [6]. Only the measures that are relevant to this paper are presented. In line with [7], the covariate factor of workload was measured using subjective, self-report scales. Mental workload was measured using a modified uni-dimensional Instantaneous Self-Assessment scale (ISA) [8]. Every 4 minutes, participants were presented with the ISA rating scale at the top of the radar scope and asked to select a workload rating. Several performance measures were collected during the simulation. For brevity, only one of these performance variables will be examined in this paper: UAM throughput. This variable was selected due to the important efficiency implications of this performance measure. In addition, in contrast to measures such as safety related performance measure number of conflicts accurately detected, this measure allows for greater granularity in performance measurement and can more easily infer performance in simulation settings compared to safety related measures [9]. Performance measures were recorded continuously throughout the simulation software.

E. Simulation Environment and Apparatus
The simulation was conducted in an ATC laboratory at NASA Ames Research Center. The software used to emulate the air traffic control system was the Multi-Aircraft Control System (MACS) [10]. Specifically, MACS was used to emulate the Standard Terminal Automation Replacement System (STARS) radar, used in the operation by TRACON controllers. Participant workstations were configured with a BARCO large-format display and a specialized keyboard/ trackball combination that is representative of what is currently used in air traffic control facilities. Voice communications via radio were enabled by a custom, stand-alone system that is also representative of what is used in operations. Data were collected continuously through MACS's data collection processes. For this study, the laboratory was configured to represent DFW tower, DAL tower and ADS tower. Traffic outside the sectors of interest were handled by confederate positions. Pseudo-pilots also used MACS in another part of the laboratory to control aircraft movements. Each simulation session lasted for 40 minutes. UAM traffic were configured to represent a single engine, electric rotorcraft, with a performance profile similar to a Cessna 172 Skyhawk. The speed range was 70-156 knots (indicated airspeed) with a cruise speed of 130 knots.

F. Participants
A total of six retired controllers took part in the simulation, consisting of 4 males and 2 females. Controllers working the DFW and DAL positions were recently retired from DFW tower control. Demographic information was not recorded.

G. Procedure
Participants were asked to work the traffic according to the conditions and procedures described in Section C. It was emphasized that the participants could work any of the traffic at any time, as they normally would. Controllers were encouraged to not let UAM aircraft enter a sector if they felt it was unsafe to do so or could result in an overload situation. In addition to the primary tasks, participants were prompted to rate their workload every four minutes for the duration of each run. The study was run over five consecutive days. Half of the first day was devoted to classroom training on the study environment and procedures, with a subsequent half day training on simulated positions prior to each set of conditions (conditions C1-3, conditions CL1-3 and conditions M1-3). After training, experimental runs were started and data were collected. Beginning on the second day, participants worked 22 data collection runs (21 planned runs and one repeat). Participants completed questionnaires at the end of each run, as well as a post-simulation questionnaire. The last session on the fifth day was a debrief that provided an additional opportunity for participants to offer feedback. Data from workstation logs and controller responses were analyzed.

III. Results
The following section presents detailed results of descriptive and inferential statistical analysis. For a discussion of findings, including interpretations and implications, please refer to the discussion (section IV).

Average subjective workload is first considered across conditions, followed by efficiency-related metrics of UAM traffic count and percentage of UAM traffic controlled. For each data set, the effect of traffic density is considered, followed by the effect of the experimental conditions (created by combinations of route and communication variables).

A. Subjective Workload

Subjective workload was measured throughout the study at four-minute intervals, resulting in 10 workload scores across the 40-minute run. Average workload ratings for each condition, as well as for individual and collapsed controller positions, are presented in Table 3, and will be referred to throughout sections A1-4.

Table 3 Means and standard deviations for workload (as rated by ISA) for all conditions and controller positions

Workload (ISA)	Workload averaged across controller positions (DFW, DAL, ADS)		DFW		DAL		ADS	
	M	SD	M	SD	M	SD	M	SD
Current routes (Baseline) UAM low density	2.87	0.98	3.59	0.42	3.35	0.03	1.65	0.35
Current routes (Baseline) UAM medium density	3.19	0.92	3.78	0.31	3.72	0.55	2.06	0.08
Current routes (Baseline) UAM high density	3.45	1.22	4.43	0.46	3.83	1.18	2.10	0.14
Current routes, LOA, UAM low density	1.95	0.56	2.10	0.42	2.30	0.71	1.45	0.35
Current routes, LOA, UAM medium density	2.60	0.58	3.10	0.14	2.80	0.28	1.90	0.14
Current routes, LOA, UAM high density	3.19	1.20	4.05	0.64	3.77	0.68	1.75	0.21
Modified routes, LOA, UAM low density	2.24	1.01	2.80	1.13	2.71	0.72	1.20	0.28
Modified routes, LOA, UAM medium density	2.89	1.44	2.78	0.31	4.55	0.07	1.35	0.21
Modified routes, LOA, UAM High density	3.13	1.37	4.35	0.07	3.60	0.28	1.45	0.49

1. Main Effect of Density: Subjective Workload Compared Across UAM Density

Subjective ratings of workload were considered in relation to UAM vehicle density. In order to gain an overview of the workload data trends, workload ratings were first averaged across the three controller positions included in the study: DFW Local East 3 position, Dallas Love Field Helo position, and Addison Tower position.

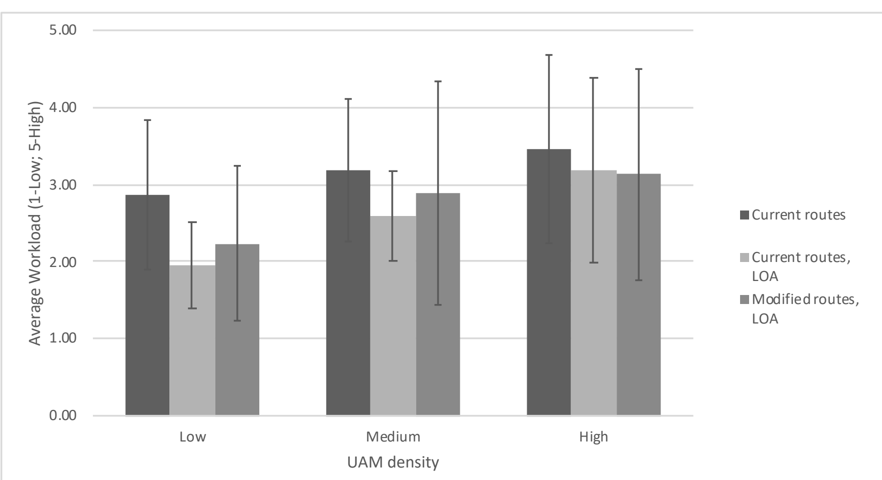

Fig. 3 Average workload and standard deviation across low, medium and high UAM densities and route condition for DFW Local East controller position

Figure 3 presents a comparison of workload data averaged across 40-minute runs, grouped by UAM density. As expected, it can be discerned from descriptive statistics (Table 3, Fig. 3) that average workload ratings increased with UAM density, suggesting that taskload affected workload as expected: C1 (current-day routes, no LOA, low UAM density) M=2.87, SD=0.98; C2 (medium UAM density) M=3.19, SD=0.92; C3 (high UAM density) M=3.45, SD=1.22). Variances are also relatively small, suggesting cohesiveness between participants' responses. The data trend of increasing average workload ratings in association with increasing UAM traffic densities is also seen in the CL conditions (current routes with LOA communications) (low UAM density M=1.95, SD=0.56; medium UAM density M=2.60, SD=0.58; high UAM density M=3.19, SD=1.20) and M conditions (Modified routes with LOA communications) (low UAM density M=2.24, SD=01.01; medium UAM density M=2.89, SD=01.44; high UAM density M=3.13, SD=1.37). It is interesting to note that the difference in workload ratings for the modified routes condition appears to be less between low, medium and high UAM traffic densities compared to the other conditions.

Inferential statistics were conducted to explore whether differences in average workload ratings between traffic densities were significant. Data were normally distributed and so a repeated measures analysis of variance (ANOVA) was utilized. For condition C, Mauchly's test indicated that the assumption of sphericity had not been violated ($X^2(2) = 2.82$, $p>0.05$). A significant main effect of UAM traffic density was found on self-reported workload ($F(2,10) = 4.65$, $p<0.05$). Pairwise comparisons did not reveal significant differences between UAM traffic densities. However, average workload difference between low and high traffic densities approached significance ($p=0.66$). In the current day routes with LOA condition, Mauchly's test indicated that the assumption of sphericity had not been violated ($X^2(2) = 3.10$, $p>0.05$. A significant main effect of UAM traffic density on self-reported workload was identified ($F(2,10) = 9.31$, $p<0.01$). Paired T-Tests expanded on this finding. A Bonferroni correction was applied and so all effects are reported at a 0.02 level of significance. Pairwise comparisons revealed that average workload ratings were significantly lower in low density traffic compared to medium density traffic ($p=0.01$) and high-density traffic ($p<0.05$). No significant differences in average workload were found between medium density and high-density traffic ($p= 0.1$). In the modified routes conditions, Mauchly's test indicated that the assumption of sphericity had not been violated ($X^2(2) = 0.29$, $p>0.05$. No significant main effect of UAM traffic density on self-reported workload was identified $F(2,10) = 2.36$, $p>0.05$.

2. Main Effect of Condition: Subjective Workload Compared Across Route and Communication Conditions

The following section considers the descriptive data presented in Table 3 and Fig. 3 but focuses on the main effect of condition across each traffic density scenario (as opposed to traffic density). Traffic density within scenarios was kept constant. For example, the same UAM traffic count was presented in the low-density scenario for all three conditions (C, CL and M).

When considering the low UAM density condition, there appear to be differences between C (current day route, no LOA) CL (current day routes, LOA) and M (modified routes, LOA) conditions. Average workload ratings are highest in the C condition in (M=2.87, SD=0.98), followed by condition M (M=2.24; SD=1.01), with the lowest average workload rating reported in condition CL (M=1.95, SD=0.56), potentially indicating that LOA had an effect on reducing average experienced workload. Differences were examined for significance. Kolmogorov-Simonov normality checks revealed that condition C in the low-density traffic violated the assumption of normality, and so non parametric tests were utilized with this condition only. No significant differences were found between average workload ratings in C, CL, and M conditions in the low UAM traffic scenario. ($X^2(2) = 9.33$, $p>0.05$).

Descriptive statistics in the medium UAM traffic scenario revealed the same data trend as seen in the low-density scenario, with average workload reported to be highest in the C condition (M=3.19, SD=0.92). Average workload for the M condition was second highest (M=2.89; SD=1.44), with average workload ratings lowest for the CL condition (M=2.60; SD=0.58). The relatively large standard deviation in the modified routes condition suggests wide variability in participant responses. A repeated measures ANOVA was conducted for the medium UAM traffic scenario. Mauchly's test indicated that the assumption of sphericity had been violated ($X^2(2) = 6.24$, $p<0.05$); therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (E=0.59). Results showed that there was a no significant main effect of condition on self-reported workload in the medium density UAM scenario $F(1.12, 5.59) = 1.31$, $p>0.05$).

Finally, descriptive statistics were reviewed for the high UAM density scenario. Descriptive statistics show that again, average workload was highest in the C condition (current routes with no LOA) (M=3.45, SD=1.22); average workload for the CL condition were second highest (M=3.19; SD=1.20), and average workload for the M condition was lowest (M=3.13; SD=1.37). The relatively large standard deviation in the modified routes condition suggests wide variability in participant responses. A repeated measures ANOVA was conducted for the high UAM density scenario. The results show that there was no significant main effect of condition on self-reported workload in the high density UAM scenario $F(2,10) = 0.79$, $p>0.05$).

3. Average Workload Separated by Controller Position: Main Effect of Density
Although data trends were identified in average reported workload, the previous analysis used average workload across all controller positions. It was therefore important to explore average workload within each condition, to determine if any differences existed between condition. Average workload ratings were separated by controller positions and examined in relation to UAM traffic densities, across route conditions. Results will be reviewed with descriptive statistics only due to low participant numbers (n=2).

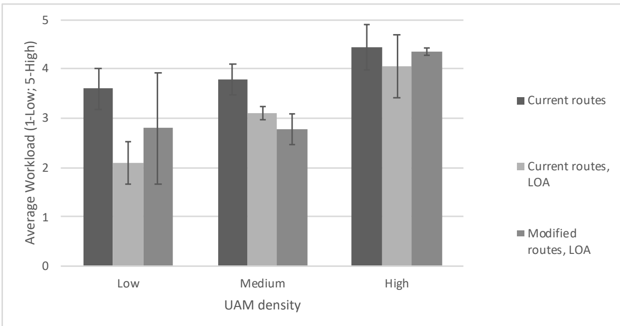

Fig. 4 Average workload across low, medium and high UAM densities and conditions for DFW Local East controller position

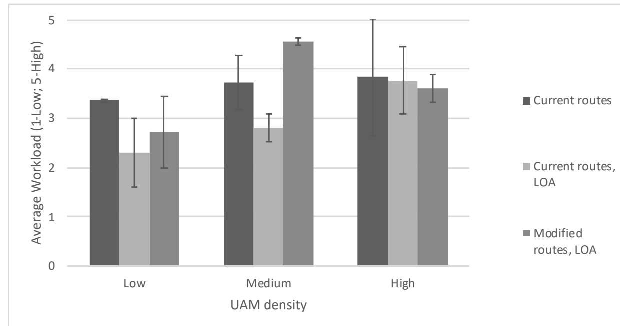

Fig. 5 Average workload across low, medium and high UAM densities and conditions for Dallas Love helo controller position

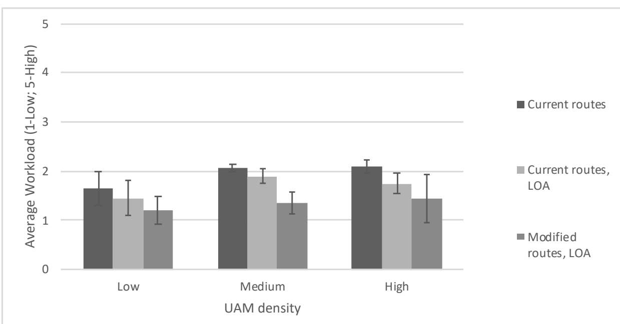

Fig. 6 Average workload across low, medium and high UAM densities and conditions for Addison tower controller position

Fig. 5 presents average workload ratings from controllers working the Dallas ft Worth Local East Tower position. A general trend can be observed where average workload increases with traffic density. Average workload was reported to be similar for both the low and medium density scenarios in the M conditions, even though the number of UAM traffic count increased. Average Workload ratings by controllers working the Dallas Love helo position also appear to be associated with UAM density (Fig. 6). In conditions C and CL, workload ratings increase as UAM traffic increases. In condition M, workload ratings go against the data trend, and appear to be higher on average in the medium traffic density scenario than the high scenario, although the workload for the high-density traffic remains similar for all three route conditions. Workload ratings for Dallas love helo position appear similar to DFW tower position, although on average, workload is slightly lower in the high-density scenario compared to DFW.

Fig. 7 presents average workload as rated by controllers working the Addison tower position. A similar data trend of increasing average workload with increasing UAMs is observed. Average workload overall for Addison tower position is lower compared to DFW and DAL positions. This is due to Addison tower not controlling as much UAM traffic as the other tower positions due to the positioning of the routes.

4. Average Workload Separated by Controller Position: Main Effect of Condition
Average workload for the DFW control position was highest in condition C (current routes with current day communications). A similar pattern can be seen in the Dallas Love position, as rated workload was highest for Condition C in both low- and high-density scenarios. Although average workload ratings for the Addison tower

position show lower rated workload compared to other control positions, a trend is observable that Condition C is associated with highest rated workload, suggesting a positive effect of both the LOA and modified routes on the reduction of subjective workload.

B. Throughput – UAM Vehicle Count

Total count of UAM vehicles controlled was recorded as an indicator of efficiency-related performance associated with each condition. The total number of UAMs for each density level (low, medium, high) remained constant across all conditions. Therefore, variances in the number of UAMs controlled between conditions were not caused by simulation artefacts. Any participant position could deny UAM traffic into Class B airspace. [7] present a detailed analysis of UAM throughput over time, but it did not extend the analysis to consider total traffic count of UAM vehicles by controller position, or compare these findings with self- reported workload collected throughout the simulation session. Therefore, the following results present an extension of findings. Table 4 and Fig. 7 present the summed total counts of UAM traffic accepted and controlled, averaged across control position. UAM count was summed for each controller across the 40-minute simulation period.

Table 4 Means and standard deviations for controlled UAM traffic counts for all conditions, averaged across controller positions

Experimental condition	Count of UAM vehicles controlled	
	M	SD
C1 - Current routes, current communications, UAM low density	51.57	33.45
C2 - Current routes, current communications, UAM medium density	55.00	38.05
C3 - Current routes, current communications, UAM high density	63.33	38.55
CL1 -Current routes, LOA, UAM low density	47.17	29.89
CL2 - Current routes, LOA, UAM medium density	70.00	41.36
CL3 - Current routes, LOA, UAM high density	92.00	60.00
M1 - Modified routes, LOA, UAM low density	50.50	35.60
ME - Modified routes, LOA, UAM medium density	71.17	47.50
M3 - Modified routes, LOA, UAM High density	96.00	68.87

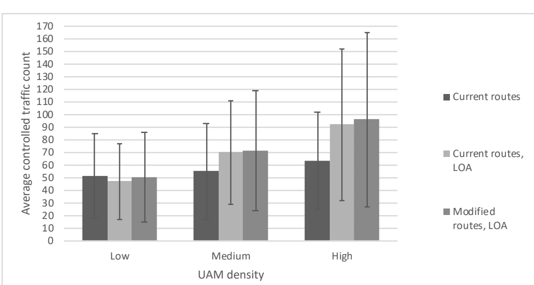

Fig. 7 Average controlled UAM traffic count across low, medium and high UAM densities and conditions

1. Main Effect of Density: Count of UAM Traffic Accepted and Controlled, Compared Across UAM Density

From a review of Fig. 7 and Table 4, it appears that, as expected, mean total of UAM vehicles controlled did increase across density scenarios for all conditions. A repeated measures ANOVA was conducted to compare differences between conditions. No significant differences were identified between total number of UAM vehicles controlled between low, medium and high traffic scenarios for condition C (current routes without LOA) ($F(2,10) = 2.12$, $p=0.17$). A significant difference was found for total UAM vehicles controlled between low, medium high-density scenarios for the CL condition (current routes with LOA) ($F(1.02,5.08) = 12.30$, $p<0.05$.) Pairwise comparisons were conducted. A Bonferroni correction was applied and all effects are reported at a 0.02 level of significance. Pairwise comparisons revealed that significantly less UAM vehicles were controlled in the low-density condition than the medium density condition ($p<0.01$) and high-density condition ($p=0.02$). The difference in controlled UAM traffic was not significantly greater in the high-density condition compared to the medium density condition ($p=0.04$). Considering condition M (modified routes with LOA), a significant difference was identified for total UAM vehicles controlled between low, medium high-density scenarios ($F(1.34,5.17) =8.36$, $p<0.05$). Pairwise comparisons were conducted. A Bonferroni correction was applied and all effects are reported at a 0.02 level of significance. Pairwise comparisons revealed that significantly less UAM vehicles were controlled in the low-density condition than the medium density condition ($p=0.01$) and approached significance between the high-density traffic ($p=0.03$). No significant differences between workload ratings were found between UAM medium density and high-density traffic ($p= 0.07$).

2. *Main Effect of Condition: Count of UAM Traffic Accepted and Controlled, Compared Across Route and Communication Conditions*

A finding of note is that although UAM traffic remained constant within density scenarios, the total count of UAM traffic controlled in each condition, within traffic density scenario, was different, due the option for participants to refuse entry to eVTOLs. It is evident from Table 4 and Fig. 7 that similar levels of UAM traffic were controlled in the low-density scenario across condition C (current route) (M=51.57,SD=33.45), condition CL, (current route with LOA) (M=47.17, SD=29.89) and condition M (modified routes with LOA) (M=50.50, SD=35.60). In the medium density scenario, fewer UAM vehicles appear to have been controlled in the C condition (M=55.00,SD=38.05) compared to the CL (M=70.00; SD=41.36) and M condition(M=71.17; SD=47.40). A relatively large difference between conditions is seen in the high density scenario, in which fewer UAM vehicles are managed on average in the C condition (m=63.33, SD=38.55) than the CL (M=92, SD=60) or the M condition (M=96.00, SD=68.87). A repeated measures ANOVA was conducted to explore differences of significance for each density scenario. No significant differences in total UAM vehicles controlled were found between C, CL and M conditions in the low-density scenario ($F(2,10) = 0.50$, $p>0.05$). In addition, the differences between controlled traffic in the medium density scenario were also not significant ($F(2,10) = 2.78$, $p>0.05$). Differences between traffic managed were significant in the high-density scenario ($F(2,10) = 5.05$, $p<0.05$). Pairwise comparisons were conducted. A Bonferroni correction was applied and all effects are reported at a 0.02 level of significance. Pairwise comparisons revealed that significantly more vehicles were controlled in the M condition compared to the CL condition ($p<0.005$).

3. *Count of UAM Traffic Accepted and Controlled Separated by Controller Position: Main Effect of Density*

Considering the results separated by controller position, a wide range of deviations around the mean (range= 29.89-68.87) suggests that there was large variation in the UAM traffic counts that were controlled by each controller position. In order to explore controlled UAM vehicle count further, the data were separated by controller position. Table 5 and Fig.s 8-10 present the averaged sum of all UAM vehicles accepted to be controlled in each condition, separated by controller position. A review of table 5 and Fig.s 8-10 reveal that a data trend is apparent for both DFW and DAL that within scenario, more UAM traffic was controlled in CL and M conditions compared to C conditions. The differences in controlled traffic count are minimal in the low-density scenario, however. This may suggest that optimized routes and reduce communications have minimal effect on performance efficiency when traffic is low. Under medium and high traffic load, these optimizations may support controllers' ability to increase efficiency performance. Unexpectedly, the same data trend was not observed for the Addison position. Within density scenarios, more UAM traffic is controlled in the CL condition compared to condition C. However, fewer eVTOLs were controlled in condition M. Route optimization resulted in changes to the UAM traffic routes through Addison airspace, so this finding is believed to be the result of an artefact of the route optimization. Inferential tests of significance were not possible due to the small n of each controller group.

Table 5 Means and standard deviations for controlled UAM traffic counts for all conditions, separated by controller positions

Experimental condition	DFW		DAL		ADS	
	M	SD	M	SD	M	SD
C1 - Current routes, current communications, UAM low density	80	4.24	64.5	0.71	9	1.41
C2 - Current routes, current communications, UAM medium density	99.5	6.36	48.5	16.26	17	1.41
C3 - Current routes, current communications, UAM high density	104.5	19.09	62.5	20.51	23	1.41
CL1 -Current routes, LOA, UAM low density	77.5	0.71	52.5	4.95	11.5	0.71
CL2 - Current routes, LOA, UAM medium density	113.5	0.71	75	1.41	21.5	3.54
CL3 - Current routes, LOA, UAM high density	158.5	9.19	92.5	6.36	25	7.07
M1 - Modified routes, LOA, UAM low density	74	11.31	72	11.31	5.5	0.71
M2 - Modified routes, LOA, UAM medium density	107	11.31	95.5	12.02	11	4.24
M3 - Modified routes, LOA, UAM High density	161.5	9.19	115	7.07	11.5	0.71

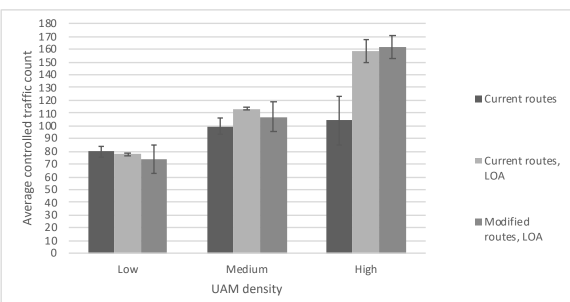

Fig. 8 Average controlled UAM traffic counts across low, medium and high UAM densities and conditions for DFW Local East controller position

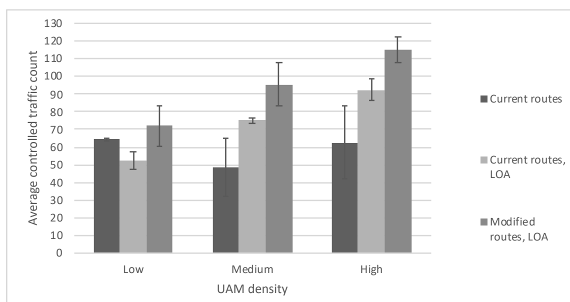

Fig. 9 Average controlled UAM traffic counts across low, medium and high UAM densities and conditions for Dallas Love helo controller position

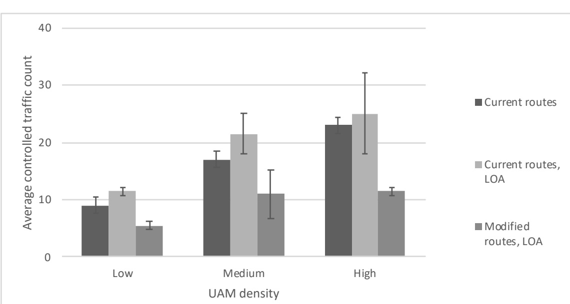

Fig. 10 Average controlled UAM traffic counts across low, medium and high UAM densities and conditions for Addison tower controller position

C. A Note on The Relationship between Workload and UAM Controlled

As the level of traffic in the scenario was assumed to be one of the main influences on workload, the relationship between perceived workload and UAM control was investigated for each scenario across experimental conditions. Due to the large number of results, not all data is represented in this paper. The relationship between workload and average UAM vehicle count was investigated using Spearman's correlations (due to a violation of independence). Table 6 shows the Spearman's correlation coefficient and associated significance level. As in the rest of the results, controller positions were first collapsed in order to examine the overall relationship.

Table 6 Spearman's correlation coefficient and association significance for controlled UAM traffic counts and average subjective workload for all conditions

Experimental condition	Spearman's coefficient	Significance
C1 - Current routes, current communications, UAM low density	0.63	$p<0.001$
C2 - Current routes, current communications, UAM medium density	0.63	$p<0.001$
C3 - Current routes, current communications, UAM high density	0.72	$p<0.001$
CL1 -Current routes, LOA, UAM low density	0.46	$p<0.05$
CL2 - Current routes, LOA, UAM medium density	0.79	$p<0.001$
CL3 - Current routes, LOA, UAM high density	-0.46	$p<0.05$
M1 - Modified routes, LOA, UAM low density	0.67	$p<0.001$
M2 - Modified routes, LOA, UAM medium density	0.68	$p<0.001$
M3 - Modified routes, LOA, UAM High density	0.69	$p<0.001$

As presented in Table 6, all relationships were significant. This suggests that there is a close covariance between reported workload and number of UAM vehicles controlled. Interestingly, in the CL condition, there is a moderately negative correlation between workload and traffic count, where workload increased as less traffic is controlled. This may indicate reduced efficiency in this condition under high destiny traffic. In order to assess the relationship further, Spearman's correlations were conducted between reported workload and traffic count for independent control positions. No relationships were found to be significant at the 0.05 level, potentially due to the low n numbers for each controller position (n=2).

D. Workload and Performance Efficiency: Percentage of UAM Vehicles Controlled

Although the previous measure of controlled UAM traffic count was an indicator of efficiency, the comparisons available were between conditions rather than to an objective value. Another method of analyzing efficiency performance was to consider the percentage of UAM aircraft accepted by controllers, compared to the total UAM aircraft available. Percentage of UAM traffic controlled was calculated by condition for each scenario, and descriptive statistics are presented in Figs 11-13. To facilitate additional consideration of the results, percentages are presented next to the average reported workload for the considered scenario and experimental condition. Presenting the data in this format supports the identification of data trends not only of percentage of traffic controlled, but also the associated workload. This also serves as a more in-depth analysis of the relationship between task demand and self-reported workload.

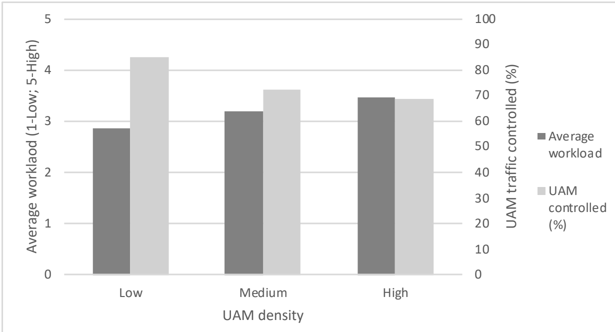

Fig. 11 Average workload and percentage of controlled UAM traffic across low, medium and high UAM densities for Condition C – current day routes and communications

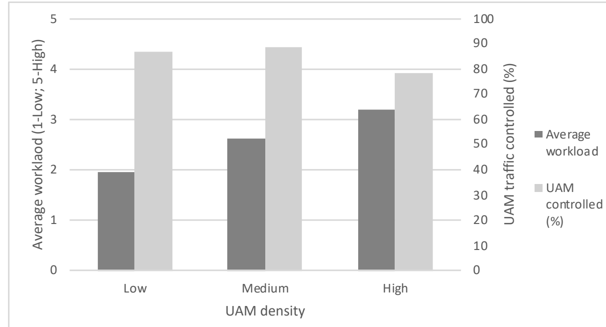

Fig. 12 Average workload and percentage of controlled UAM traffic across low, medium and high UAM densities for Condition CL – current day routes and LOA communications

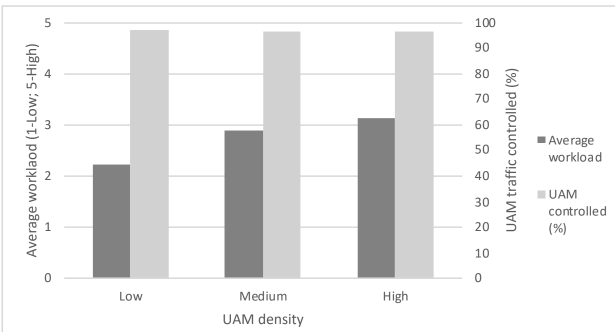

Fig. 13 Average workload and percentage of controlled UAM traffic across low, medium and high UAM densities for Condition M – modified routes and communications

As seen in Fig. 11, in the C condition, percentage of UAM traffic-controlled declines as traffic density increases. When considered with workload, an association is apparent. In the low-density scenario, workload is rated around the mean point of the scale (M=2.87, SD=0.98) with a high percentage of controlled UAM (M=84.75%). In the medium density scenario, workload increases (M=3.19, SD=0.92), whereas UAM % controlled dropped to 72.18. Finally, in the high-density scenario, workload increases further to an average of 3.45, whilst percentage of UAMs managed dropped to 68.45. In the CL condition (Fig. 12) it can be seen that the percentage of controlled UAM aircraft is higher, in each density, compared to condition C (low density =86.74%, medium density =88.79%, high density =78.15%). In the high-density scenario, percentage of controlled traffic drops compared to the low and medium density scenarios but is higher than the percentage of controlled traffic in condition C with high density traffic, again suggesting a positive effect of reduce verbal communications. In relation to condition M, the same data trend of increasing average workload with increasing traffic density was observed (Fig. 13).

IV. Discussion

A. Overview

A human in the loop air traffic control simulation was used to investigate the effect of UAM traffic density and changes in current-day airspace routes and communication procedures on subjective controller workload and efficiency-related task performance. The study explored human factors considerations for near-term integration of UAM traffic into the current airspace. Current communications, procedures and regulations surrounding class B, C and D airspace were incorporated into the simulation. Controllers managed UAM traffic based on procedures for VFR traffic in current day operations. The aim of the research was to contribute further understanding of human factors considerations and human operator roles for near-term UAM operations. Specifically, this research aimed to investigate the association between UAM traffic demand, subjective reported workload, and efficiency related performance. In addition, the research aimed to investigate the effect of route changes, optimized for UAM traffic, and the introduction of reduced verbal clearances to UAM traffic in association with workload and ATCO efficiency-related performance. A discussion of key findings is presented in the following section.

B. Self-reported workload increased with traffic density

An analysis of average self-reported workload collapsed across controller positions revealed that, as expected, workload increased with traffic density scenarios in all experimental conditions, suggesting that UAM demand created variability in self-reported workload. In condition C (current day routes with current day communications), differences between rated workload in the low- and high-density traffic scenarios approached significance, whilst in condition CL (current day routes with a LOA agreement) workload was rated significantly higher in the high-density scenario than in low density scenario. Differences in workload ratings did not reach significance in condition M (modified routes and LOA agreement). Variances were larger in this condition possibly weakening the inferential analysis.

C. Reduced communication is associated with lower workload than current day communication procedures

An analysis of average self-reported workload explored workload ratings for each experimental condition (C, CL, M) in association with traffic density scenarios. Within density scenario, traffic levels remained constant for each condition. When collapsed across controller position, a review of the descriptive statistics in the low-density scenario showed that there were differences in average perceived workload even though objective traffic counts remained constant. Overall, average workload ratings for condition C were higher than for conditions CL or M, in all density scenarios, suggesting that the reduction of verbal communication and optimized routing had a positive effect on subjective workload. The differences between average workload in conditions CL and M appeared to be minimal. This may suggest that workload was most positively affected by the reduction in verbal communications; however, although the workload seems to be similar for CL and M conditions, the amount of traffic controlled in M seem to be higher, thereby suggesting that workload per aircraft might be lower in condition M.

This finding was robust, and was repeated across individual controller positions. Overall, a data trend was identified for each controller position that on average, workload was reported to be higher in condition C than conditions CL and M. Unfortunately, tests of significance could not confirm this trend due to low participant numbers. Whether workload was rated higher in condition CL or M appears to depend on both controller position and traffic density. A regular pattern was seen for Addison control that workload in condition M was reported to be lower than condition C or CL; however, this pattern was not as regular in DFW or DAL positions. Specifically, for the DFW position, the M condition was rated higher for workload than the CL condition. This may have been due to a lack of familiarity with the modified routes compared to experience with the current day routes. The difference between workload ratings for conditions CL and M was marginal however, suggesting that both conditions had a similar effect on subjective workload. Although Addison tower position reported the lowest average workload, condition still appeared to influence workload ratings, with reported workload highest in condition C and lowest in condition M. This suggests that even in periods of lower task demand and associated workload, the LOA and modification of routes may still have a positive effect on the reduction of workload. However, the differences between average workload were relatively small for all conditions, indicating that the positive impact was not as marked as in higher density scenarios. Overall, average workload data trends and the finding that condition C, representing current day routes and communications, resulted in the highest reported subjective workload for all positions, conditions and scenario densities, indicates that the traditional procedures and regulations may not support scalable UAM integration in controlled airspace.

D. Current day routes and procedures were associated with fewer controlled aircraft than other conditions

Differences in controlled UAM traffic counts were seen in the results as participants were given the option of refusing entry to eVTOLs if safety-related performance or overload were a concern. The average count of controlled UAMs remained similar in condition C for all scenario densities, suggesting that a ceiling effect was reached for the amount of traffic that participants were willing to control, regardless of the amount of traffic requesting access to controlled airspace. This effect is not seen in conditions CL and M, in which more traffic is controlled in the medium and high-density scenarios compared to the low-density scenarios. This may suggest that the reduced communication and modified routes enabled participants to control more traffic compared to current day routes and communications.

Considering data across conditions, in the low UAM density scenario, no significant differences were found between conditions for the average count of controlled UAM traffic. This suggests that controllers managed to control all UAM flights that were available in the low-density scenario, identifying a potential limit capacity. In the medium density condition, on average, less eVTOLs were accepted for control in the current route condition compared to the CL and M conditions, although differences were not found to be significant. This data trend suggests that the provision of reduced communications via and LOA and modified routes enabled controllers to accept more UAM traffic into controlled airspace, whereas the use of current day routes and communication procedures without a LOA restricted efficiency performance for UAM traffic. The lower number of controlled UAM traffic in condition C may be associated with the consistently higher average workload in condition C, resulting in more rejected more eVTOL requests.

A comparison of descriptive data for each controller position revealed the same data trend in both DFW and DAL positions, but was not observed in Addison to such an extent. Potentially, the lower average workload experienced by participants working Addison airspace prevented the same limits to the amount of controlled aircraft being observed. Participants controlling DFW positions appeared to control similar counts of UAM traffic in conditions CL and M, suggesting a greater impact of communication reduction on capacity to accept traffic, as there was no marked effect of including the modified routes identified in the data. However, differences between the average count of controlled UAMs between CL and M conditions were greater for DAL tower position, with more traffic accepted in the M condition than the CL condition, in all traffic densities. This finding potentially indicates that for the DAL position, the inclusion of modified routes in addition to the communication LOA supported controllers' capacity to control UAM traffic to a greater extent than the use of the LOS without the modified routes. This finding may be explained by considering the specific modification to the routes, as well as workload data. When considering the workload data in conjunction with the average count of controlled UAM traffic, it can be seen that average workload rated by participants in the DAL control position was lower than that reported by participants in the DFW position, especially for the high-density traffic scenario. There is a well-established relationship between workload and traffic capacity (e.g. 13, 14) with sector capacity limitations one of the operational methods used to prevent overloads. It may therefore be suggested that the lower workload reported for the DAL position compared to the DFW position may have enabled the effect of modified routes to increase capacity to control UAM traffic. However, the higher workload experienced in DFW position may have been too high for any benefits afforded by modification of routes to affect workload to an extent that capacity was increased, compared to the more direct reduction of workload achieved through the use of a LOA. It may also possible that the optimization of routes through DAL airspace resulted in a greater reduction of workload, and associated increased in capacity, compared to DFW, although this possibility requires further exploration. In contrast to DFW and DAL, average traffic count documented in the M condition for the Addison tower position, was consistently lower than both C and CL conditions, across all density scenarios. This finding can be explained as an artefact of modifying the UAM routes, diverting UAM traffic out of Addison airspace to avoid further regulations for entry to controlled airspace. Overall, findings suggest that reducing communications and modifying current day routes can positively effect control capacity, at least in association with specific airspace features, possibly due to a reduction in workload.

E. Route optimization may moderate the association between workload and controlled traffic

A second metric of efficiency-related task performance, specifically, percentage of UAMs accepted into controlled airspace, was utilized to further explore the effect of experimental conditions and UAM traffic density on workload and performance. In condition C, a negative association is inferred between workload and percentage of UAM aircraft controlled across scenario density, as the percentage of controlled traffic reduced as average workload increased. This result can be explained by participants rejecting UAM traffic from entering controlled airspace, as they were permitted to do if they perceived more traffic was unmanageable or could potentially result in an overload. In condition CL, descriptive statistics showed that the percentage of UAM vehicles controlled was higher for all density conditions compared to condition C, reinforcing the suggestion that that participants may have found it more manageable to control higher percentages of traffic with the reduction of verbal communications via a LOA. An interesting point to note is that the association between workload and the percentage of controlled traffic appears to be weaker compared to condition C. Percentage of controlled traffic remained stable for low and medium density conditions, although average workload is reported to rise. A reduction in the percentage of controlled traffic is seen in the high-density condition, with a further increase in reported workload. This may be explained by the effect of the LOA. Although workload increases across density, overall workload is lower for all densities compared to condition C. It may therefore be suggested that the introduction of the LOA reduced overall workload so that even when workload increased in the medium density condition compared to the low-density scenario, participants still had capacity to control a higher percentage of traffic. When workload increased further in the high-density condition (to an average reported in condition C) the percentage of controlled traffic dropped, indicating that even with a LOA, this level of workload was associated with an increase of refusals to accept traffic. In condition M, the percentage of controlled UAM traffic is higher than in the C or CL conditions. Percentage of controlled traffic remained consistently high in all density scenarios, even though workload ratings progressively increased with increased traffic density. In contrast to conditions C and CL, there does not appear to be an association between percentage of traffic controlled and reported workload. The use of modified routes in addition to a LOA may have acted as a moderator of this relationship, allowing a high percentage of traffic to be controlled even with increasing workload.

F. Route modifications are associated with increased traffic, although not necessarily reduced workload

Workload appeared to be similar for CL and M conditions, although the amount of traffic controlled in M, as reported by traffic count and percentage of traffic controlled, appears to be higher. In consideration with previous findings, it is especially interesting to note the association between workload, average traffic count and percentage traffic controlled. Previous workload findings suggested that modified routes may have had less impact on workload reduction compared to the inclusion of a LOA. However, by interpreting the finding in relation to percentage of traffic controlled, it appears that the inclusion of optimized routes may enable a higher percentage of traffic to be controlled, at a similar level of workload other conditions. Modified routes may not necessarily have had an effect on workload directly, but instead may have influenced workload influencing factors, such as traffic complexity. More direct routes, with greater separation between modified UAM traffic routes and commercial traffic, may have allowed controllers to accept greater UAM traffic counts into controlled airspace whilst minimally affecting workload. Although this suggestion will need further investigation prior to confirmation, it is a plausible explanation which can account for the presented findings. Overall, findings suggest that reduced verbal communication and modified routes may have a positive effect on efficiency related metrics of performance.

G. Positioning of UAM routes has implications for workload

It was acknowledged that there were large variances in average workload around the mean, especially in the high-density scenario, indicating different workload was experienced between controller positions. It was evident from a review of descriptive statistics that Addison tower position was reported to result in the least average workload. Specific to the Addison control position when the routes were optimized the change fundamentally changed Addison's job and it appeared to benefit the most out of all positions.

Due to the position of Addison tower, fewer and shorter UAM traffic routes passed through this airspace. This finding provides an important reminder that the future positioning of UAM traffic routes should take into account the potential influence on UAM operator workload, as well as workload experienced by ATCOs working commercial traffic depending on how UAM routes interact with current day routes. DFW tower position on average had the highest workload ratings. Future studies that utilize the airspace in the Dallas metroplex area should focus particular attention on the effect of UAM traffic on this position. The airspace is complex and often result in high task demand in current day operations, and the integration of UAM traffic has the potential to increase task demand and therefore workload, with potential negative associations with ATCO performance. An area of future research therefore, is the identification of workload-influencing factors that are associated with the integration of UAM traffic in the airspace, and the prevention or mitigation of these factors on ATCO performance.

V. Conclusion

A human in the loop air traffic control simulation was used to investigate the effect of UAM traffic density, airspace routes and communication procedures on subjective workload and efficiency-related task performance. Findings indicated that medium and high-density operations were associated with high workload. A reduction in verbal communications through a letter of agreement, and optimized routes, were associated with reduced workload and increased performance efficiency. However, even with these adjustments, the scalability of UAM operations would remain restricted relative to the envisaged mid and far-term operations. Future research should focus on the human operator roles and responsibilities, and the amount of involvement, in UAM system management. Particular focus should be directed on the impact of reduced human operator involvement and increased automation, on the safety and efficiency of UAM operations and the integration of UAM with traditional air traffic management.

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