Effect of Airspace Characteristics on Urban Air Mobility Airspace Capacity

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As interest in urban air mobility grows, increasingly high density traffic poses a challenge for the transition to safe, efficient, and timely operations. Hundreds of simultaneously demanded flights will need to share the same fleet, infrastructure, and constrained airspace. This paper investigates the feasibility of effectively managing high density traffic in congested urban environments by optimizing the design of airspace route structures. Demand estimations for the Dallas-Fort Worth and Los Angeles areas are used to evaluate potential improvements to airspace route design with the goal to accommodate the projected level of demand.

I. Introduction

As progress is made towards the start of Urban Air Mobility (UAM) operations, it is important to anticipate issues that may arise as the quantity of operations grows. Some of these issues are societal, such as the acceptance of travel using small, potentially unmanned aircraft, and others are related to the business case, such as the anticipated demand dependent on the cost of travel. However, many potential issues relate to how these vehicles operate and the rules and procedures that govern them.

NASA's Air Traffic Management - eXploration (ATM-X) Project aims to address some of these challenges through focused research [1]. In particular, the UAM subproject focuses on the technologies and architectures for airspace and vertiport management that will enable widespread UAM operation [1, 2]. Examples of research goals include safe mission planning and operation, separation assurance, dynamic scheduling, congestion management, and interoperability with other air traffic [1]. One particular area of interest is congestion management, specifically concerning how to safely meet the anticipated demand of high density areas without causing undue delay or cancellation of flights.

Others have previously studied the constraining factors involved with airspace in the commercial aviation and small Unmanned Aerial System (sUAS) sectors. Xue describes the use of corridors in the sky or "tubes" to reduce controller workload and increase the capacity of a given airspace and then expands to further study the effects of fuel and complexity associated with this concept [3, 4]. A method was proposed utilizing a non-dominated sorting genetic algorithm (NSGA) to reduce the amount of delay experienced due to scheduling in terminal airspace. Xue and Rios also created a fast time simulation tool capable of modeling sUAS operations to test the impact of various parameters, rules, and models, and evaluate them statistically in realistic environments [5, 6].

This paper explores how different routing structures, such as those described in Ref. [7], can affect the total number of operations successfully performed in a given metropolitan area. The quantity and distribution of demand is typical of UAM Maturity Level 4 (UML-4) operations. UMLs detail the progression of UAM operations within the NAS, from pre-operational to ubiquitous and wide-spread use [8–10]. Traffic demand scenarios, generated by the Virginia Tech Air Transportation Systems Laboratory are used as a reference case for realistic demand, with variations due to time of day and vertiport location [11–14]. Initial airspace designs, including airspace where UAM traffic will not be able to operate, were created by the ATM-X UAM Airspace and Procedures Design Team. By combining the scale of operations with this minimally modified existing airspace, potential capacity limits can be identified and improved upon.

Two tools were used to simulate an airspace and provide pre-planning conflict detection and resolution. These tools are described in Section II. The airspace and traffic demand scenarios for the Dallas Fort-Worth and Los Angeles regions, generated by Virginia Tech and the ATM-X project, are then presented in Section III. Route structures for the two regions, generated using the results from Denham et al., are described in Section IV and analyzed for improvement of airspace capacity compared to the initial structure in Section V. The paper ends with a summary, areas of future work, and the potential impact of this research.

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II. Analysis Tools

A. ATS-TIGAR

The ATS-TIGAR tool created at NASA Langley for the ATM-X UAM subproject provides real-time trajectory planning simulation, including conflict detection and resolution [15]. Many factors pertaining to trajectory planning, such as separation volumes, airspace restrictions, route structure, resolution method, and maximum allowable delay, can be modified. The scenario input files determine other demand characteristics including the timing of requested flights, the number of landing pads at each vertiport, the number of parking spaces at each vertiport, and the total number of vehicles in the fleet.

The ATS-TIGAR tool outputs two text files, one which contains the flight information and optional trajectory data for each flight in the scenario file, and a second which contains the mission planner information. To aid in the analysis of these files, several MATLAB® scripts were written to parse the data and put it into a format that is both machine- and human-readable. These scripts include metadata for the run including the scenario, simulation type, airspace type, separation volume, and fleet size. These utilities facilitated comparison and visualization of the data.

Several tactics were used within ATS-TIGAR simulations to study the effects of airspace design in isolation. First, a baseline run with a reasonable fleet was compared to a run with an impossibly large fleet. The large fleet effectively removed the need for repositioning flights, therefore allowing study of the demanded flights in isolation.

B. Airspace Routing, Conflict, and Scheduling Simulation (ARCSS)

The Airspace Routing, Conflict, and Scheduling Simulation is a tool developed in MATLAB®, which enables quick simulation and evaluation of airspace route structures, conflict resolutions, and scheduling protocols. It uses a pre-planning approach to detect and resolve conflicts before determining an aircraft's trajectory, as opposed to detecting and resolving conflicts in real time during a simulated flight. The tool also includes the ability to detect conflicts without resolution so that the effect of resolution can be determined. This approach enables testing of conflict avoidance strategies without requiring a high fidelity simulation of the aircraft dynamics or substantial computational power. Figure 1 shows an example from a typical ARCSS simulation, including vertiports, airspace constraints, UAM vehicles, and the conflict notification bar which displays an instantaneous number of affected aircraft in the event of loss of separation between aircraft or violation of airspace constraints. Currently, the primary method of conflict resolution is to add an on-ground departure delay but other strategies such as altitude changes, horizontal trajectory changes, or speed changes are possible.

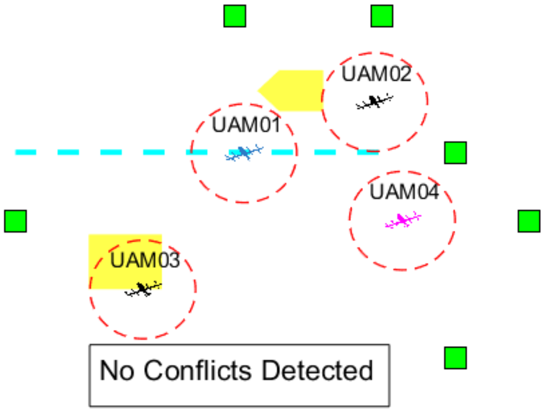

Fig. 1 Screenshot of ARCSS, including vertiports (green squares), airspace constraints (yellow shaded region), defined route (blue dashed line), UAM aircraft, and conflict notification bar.

III. Realistic Airspace and Traffic Demand Scenario Generation

Demand for UAM flights was estimated by the Virginia Tech Air Transportation Systems Laboratory to create a set of scenarios at various demand levels for study. These demand estimates were based on an economic assessment of the demand for UAM in the Dallas Fort-Worth (DFW) and Los Angeles (LAX) regions using cost assumptions appropriate for technological advances expected in the next 15 to 20 years. It was also assumed that the aircraft would not require a pilot. Even under these optimistic assumptions, the model did not yield sufficient demand to reach UML-4 scale operations on the order of hundreds of simultaneous flights. To reach the desired level of demand for this study, the model was adjusted to lower ticket prices below the estimated lower bound. Three categories of trips were included: commuters, airport passengers transiting to and from the commercial airports, and some initial estimated high urgency cargo being distributed from the commercial airports.

A. Dallas-Fort Worth Scenario

The Dallas-Fort Worth area was selected for this analysis because of early interest from industry, favorable weather conditions, flat terrain, significant ground congestion, and the potential economic demand for quicker transportation systems. This region has also been previously studied in the literature and therefore significant background information was readily available. The number of each category of UAM trips calculated by Virginia Tech is shown in Table 1, with the majority of the trips being either commuter or airport trips.

The airspace above the DFW region is busy as the region contains multiple class B and D airports, several of which are host to large numbers of daily commercial and general aviation flights. A set of airspace constraints and UAM routes were designed by the Airspace Procedures and Design Team of the ATM-X UAM sub-project to procedurally deconflict UAM flights from commercial airline traffic. Due to the large amount of class B airspace in the center of the region, UAM flights are forced to make significant detours to avoid restricted airspace or fly along specifically created narrow routes. Outside of the dense central area, the route structure is not required and UAM aircraft can fly direct paths between either their departure and arrival vertiports or a vertiport and the border of the route structure.

Figure 2 shows the UAM airspace design for the DFW region. Airspace constraints are shown in yellow and vertiports are represented as green squares with the number of squares indicating the number of vertipads. The route structure is indicated by the light blue lines and is defined by the intersections labeled in purple.

Table 1 24 Hr Demand Distribution for DFW Region

Trip Type	Quantity
Commuter	3404
Airport	1890
Cargo	402
Total	5696

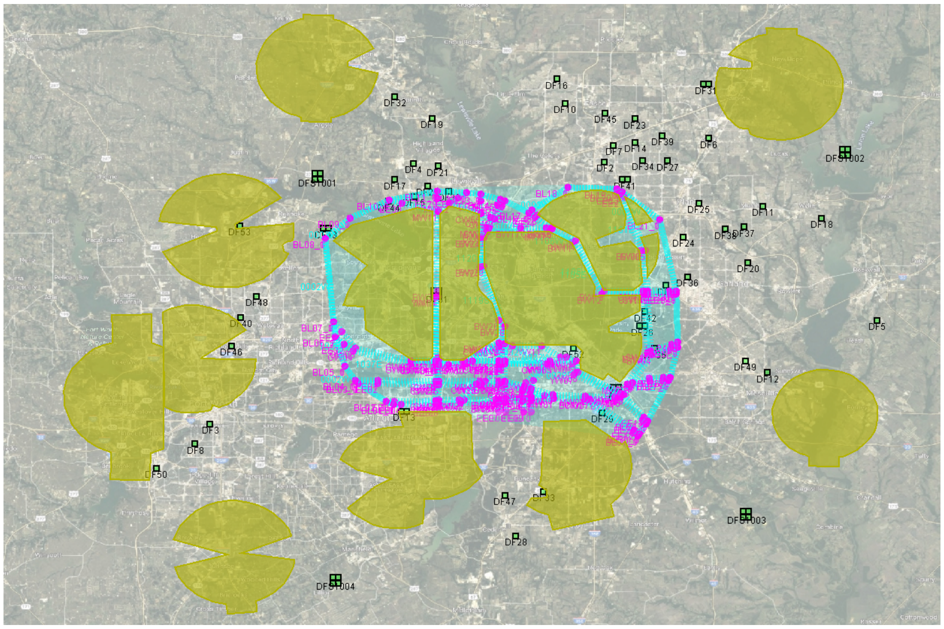

Fig. 2 DFW airspace structure, including airspace constraints, vertiport locations, and initial route structure.

Vertiports were placed based on estimated demand throughout the DFW region. In total, 49 regular vertiports, three airport-shuttle vertiports, and four depot style aircraft storage vertiports were included in the simulation. The number of parking spaces and vertipads included at each vertiport was based on the expected level of demand at that specific location. The majority of vertiports in the network only have one vertipad, although the busiest vertiports have four. Depot style vertiports have six pads, unlimited parking, and are envisioned as the location where aircraft maintenance and long-term storage will occur.

An important factor discovered in the demand study was that some vertiports account for a much higher portion of the demand than others. Figure 3 shows the distribution of daily flights among the 56 vertiports in the DFW area. The three busiest vertiports account for 61% of the total daily departures and arrivals. Most notably, the DF51 vertiport located at the DFW airport terminal is responsible for 36% of the daily demanded trips. Not only does this vertiport handle a large portion of the airport trip demand, but it also receives commuter and cargo demand due to its location. However, because the vertiport is located in the "spine" between two airspace constraints, flights into and out of the vertiport are highly constrained.

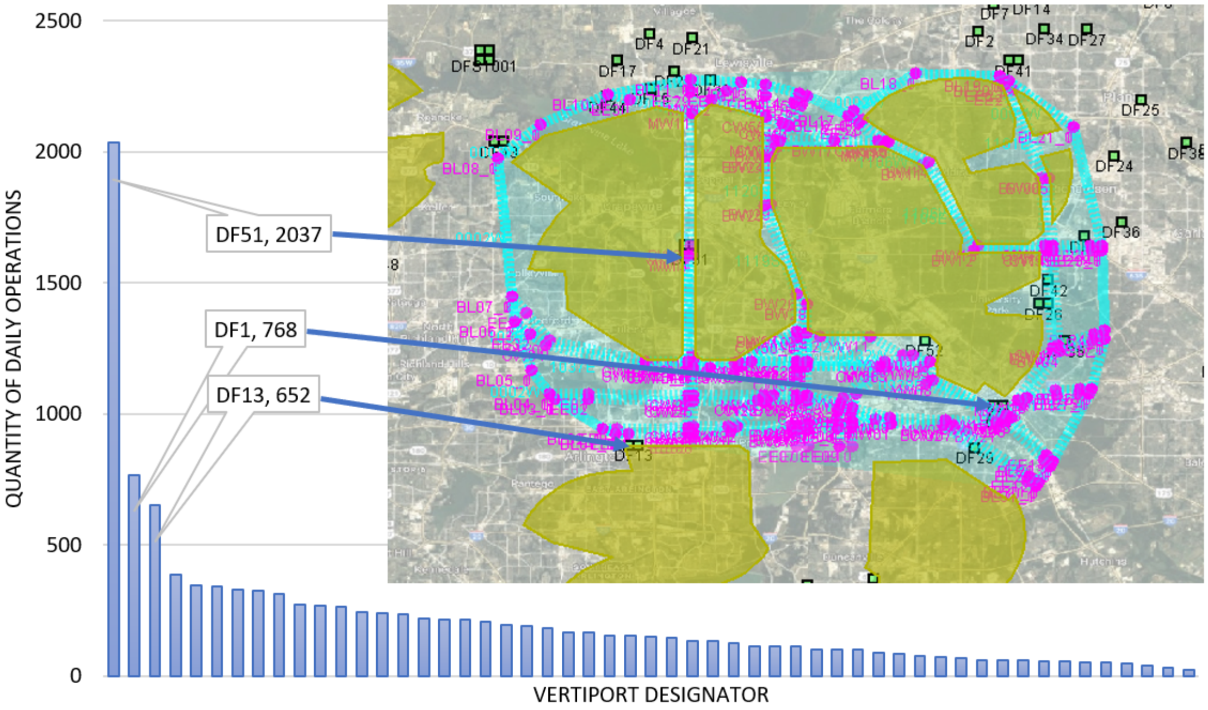

Fig. 3 DFW vertiport demand distribution.

B. Los Angeles Scenario

The second study area considered for this work was the Los Angeles region. This region could be attractive to UAM operations due to the amount of ground traffic congestion combined with potential demand from individuals with a high value of time. One possible advantage is the somewhat reduced complexity of the airspace compared to DFW, allowing for better utilization of airspace by UAM flights. This scenario, shown in Fig. 4 does not have a potential route structure defined by the Airspace Procedures and Design Team, providing an opportunity to design an efficient structure based on demand, airspace constraints, and vertiport locations. The creation of this route structure is discussed further in Sec. IV.B.

The total quantity of operations predicted in the LAX region was similar to the DFW region. The busiest vertiport was once again located at the airport, but access was much easier than in the DFW region due to the wide cutout in constrained airspace to the north of the airport.

Table 2 Demand Distribution for LAX Region

Trip Type	Quantity
Commuter	2624
Airport	3084
Cargo	439
Total	6147

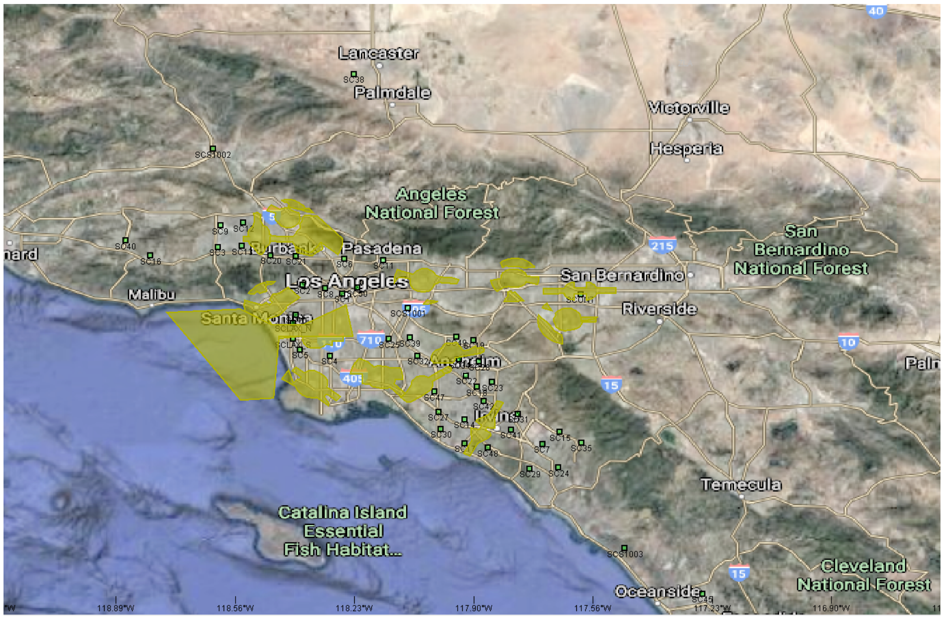

Fig. 4 LAX airspace structure, including airspace constraints and vertiport locations.

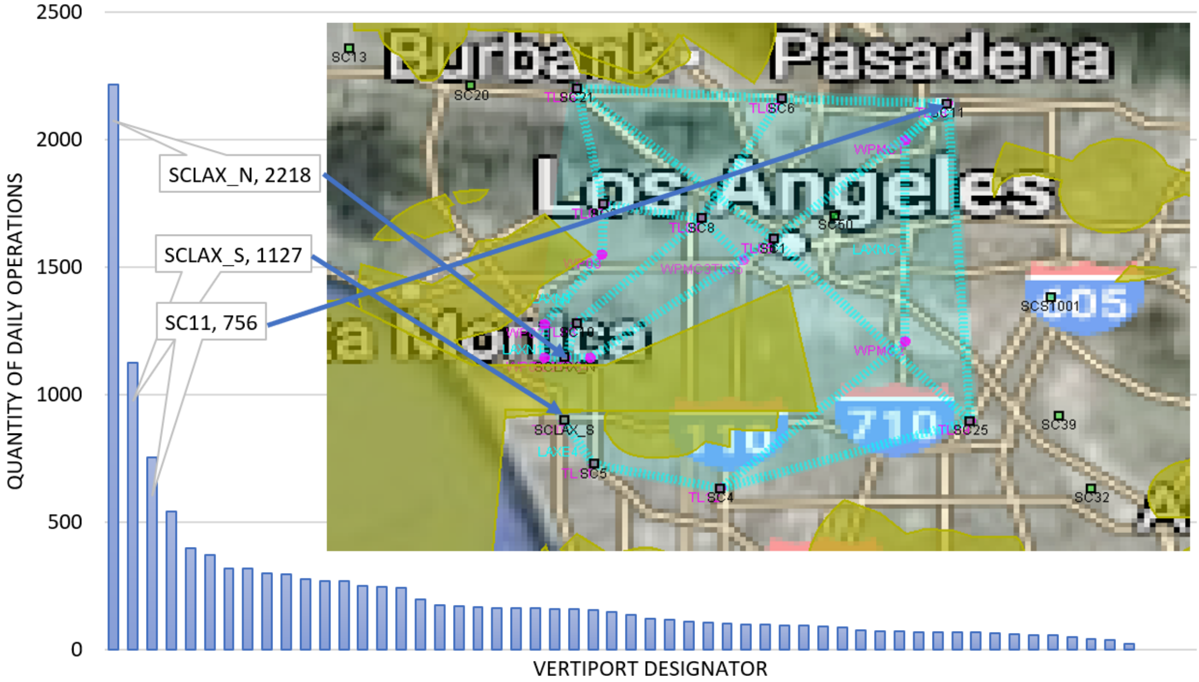

Fig. 5 LAX vertiport demand distribution.

IV. Updated Route Structure

A. Dallas-Fort Worth Updated Route Structure

The DFW spine route is a significant capacity constraint because the long, narrow corridor creates a bottleneck, since it is only wide enough to have a single flight operating at a time. If a flight needed to travel the opposite direction along the spine route, it would have to be delayed until the first flight is out of the spine. This constraint significantly reduces the number of flights that are able to use vertiport DF51. One potential solution is to remove the vertiport from the airport in the middle of the corridor and replace it with two new vertiports, one each at the north and south end of the spine, as seen in Fig 6. This allows the airport demand to be captured without significant changes to the route structure but does impose an additional travel segment for passengers to move from the vertiport to the airport terminal. In the future, this layout could be supplemented by an automated train to enable this final leg. To implement the split vertiport layout in this scenario, the traffic that had originally been destined for DF51 was moved to either the north or south vertiport based on its originating latitude. Departures north of 32.93° N, just north of the airport, were routed to the north vertiport and vice versa for the south. The same approach was used to re-distribute the flights originating from DF51.

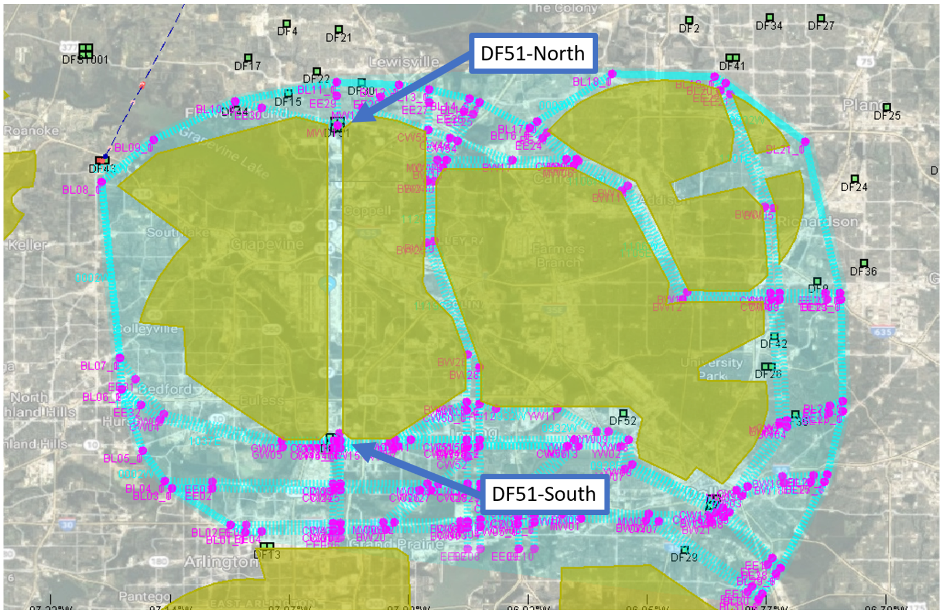

Fig. 6 DFW vertiport DF51 split into north and south vertiports.

Another approach to alleviate some of the UAM traffic congestion along the spine route is to widen the spine, allowing traffic to pass through in both directions simultaneously. For the sake of this study, the two routes built into the airspace were moved to be parallel with 2000 ft spacing between them, wide enough to allow some maneuvering during approach to the vertiport without impacting the other route. The north end of the spine still contains a single path but is not as highly congested as the south. An example of traffic flowing in both directions through the spine is shown in Fig. 7. The airspace polygon constraints were not modified for this case, only the routing structure. However, no analysis of wake turbulence or runway separation has been performed, so further analysis needs to be completed to determine the feasibility of this airspace modification.

B. Los Angeles Route Structure

Since there was not an existing route structure for the Los Angeles region, an attempt was made to design a route structure specifically based on the findings from the companion paper [7]. Building up to this, several intermediate route structures were created for the sake of comparison. All of these structures were designed around the 10 vertiports with the highest quantity of daily demand. The first structure featured simple, straight line bi-directional routes that connected each of the 10 vertiports except where needed to bend around airspace constraints. The second structure moved to reduced the number of obtuse intersections and decreased the total number of routes. The final route structure shown in Fig. 8 featured most of the same routes as the second structure but included two special routes created with the goal of enforcing orthogonal intersections.

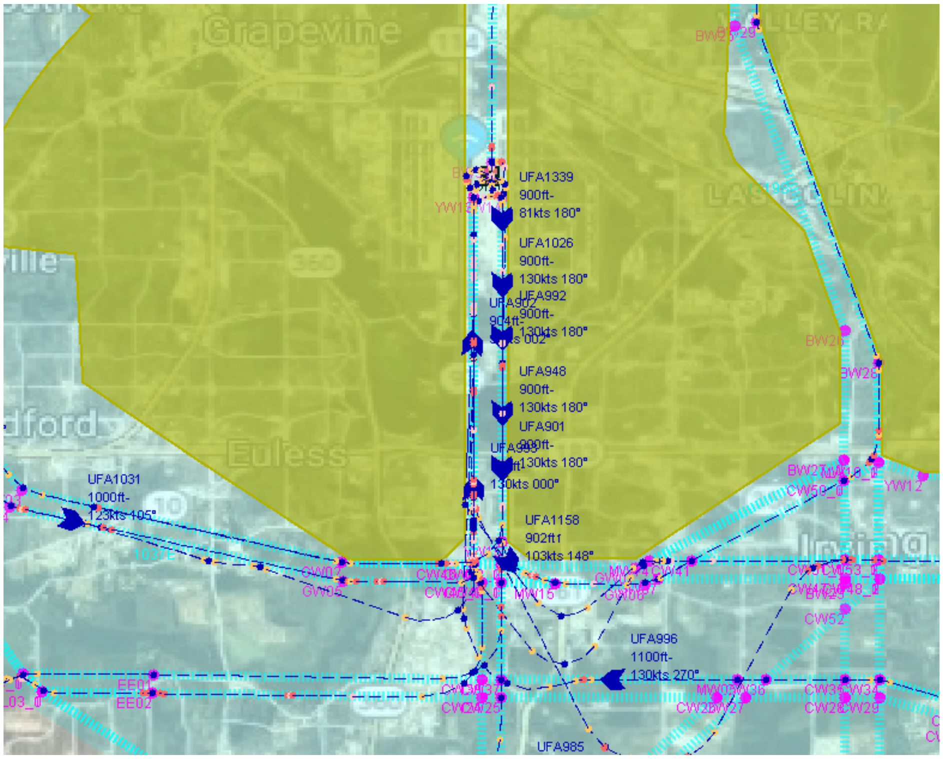

Fig. 7 DFW widened spine with simultaneous flow.

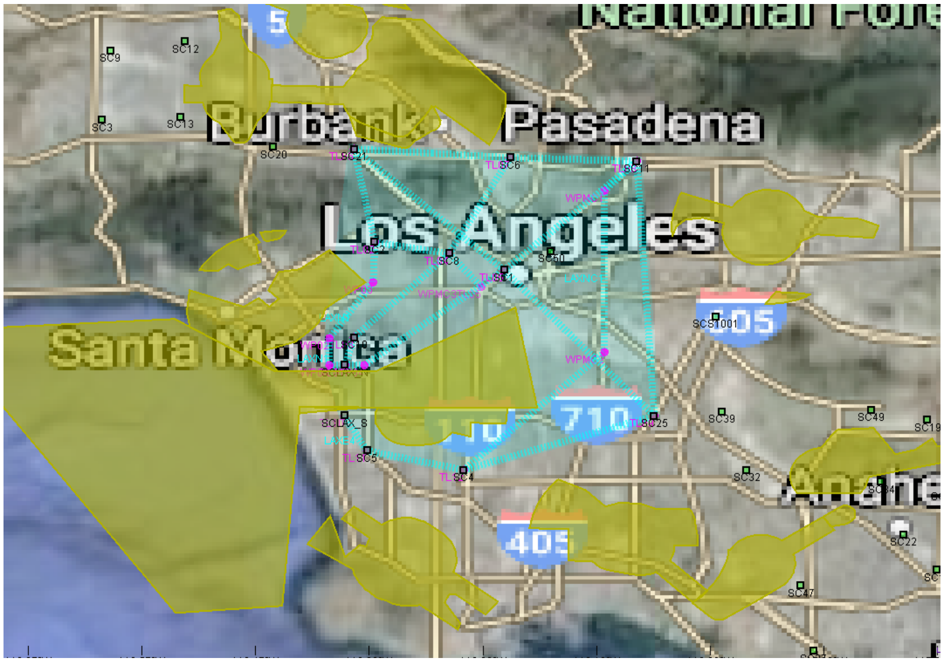

Fig. 8 LAX Purpose Designed Route Structure.

V. Comparison of Capacity for Initial and Updated Route Structure

A. Airspace Capacity Metric

Airspace capacity is defined by the maximum number of operations that can be achieved for a given airspace volume, design, and demand scenario. For this study the demand scenario and airspace volume are held constant. The maximum number of operations is quantified by comparing the average delay and the number of flights canceled due to excessive delay, defined as exceeding 900 seconds. For UAM, the airspace volume is typically comprised of an urban center and its surrounding metropolitan area. Airspace design consists of all the airspace above the region, with design features including cutouts for commercial and general aviation traffic, vertiport placements, and commonly used routes. Although the separation volume is an important factor in determining airspace capacity, it is dependent on the safety case and is not a feature of the airspace. For this analysis, nominal values were used for the radius and height of the volume. The unequal distribution of traffic demand is another factor which affects airspace capacity. The demand scenarios used for this work were developed by Virginia Tech as described previously.

To take a closer look at smaller sections of airspace and individual intersections in the DFW airspace, a set of control volumes was defined that captured the activity at areas of interest in the DFW route structure. The total number of flights passing through these volumes was tracked throughout the TIGAR simulations and compared against ARCSS simulations and against the theoretical maximum capacity for the intersection type and geometry. These control volumes are shown in yellow in Fig. 9. Traffic flow direction is shown by the light blue arrows positioned on top of each route. Traffic was measured during each hour of the simulation but only the maximum values experienced during peak demand times are shown in the results to follow.

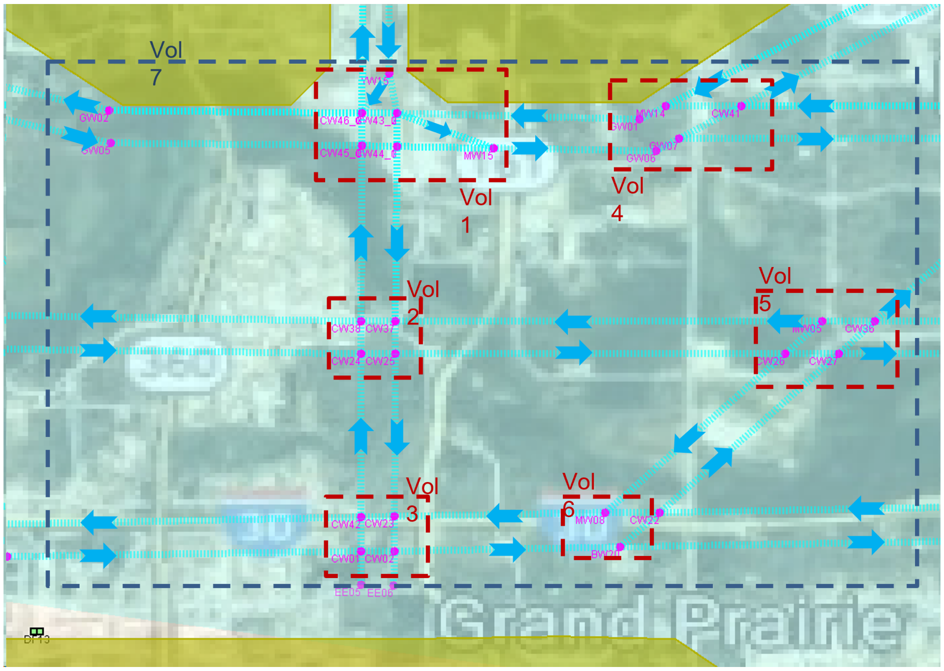

Fig. 9 DFW Control Volumes.

Volume 1 contains the intersection at the south end of the spine route. This critical intersection transports all of the traffic that enters and exits the spine as well as any traffic moving east and west across the south end of the airspace constraint. To facilitate smoother flow into and out of the spine, two connector routes provide paths for turning traffic. Volumes 2 and 3 are simple crossing intersections. Volumes 4, 5, and 6 are built mainly from converging and diverging elements but also feature some angled crossings that enabled east or west-bound traffic to move efficiently to the neighboring north and south-bound routes. The entire area is bounded by a large volume that tracks all of the transient traffic. Throughput for each of these volumes is shown in Table 3. Results from each TIGAR simulations are shown alongside the idealized case from ARCSS and finally a computed theoretical maximum value.

Table 3 DFW 1 Hr Maximum Control Volume Throughput Measured Values

Volume	Small Fleet	Large Fleet	Split Vertiport	Wide Spine	ARCSS	Theoretical Max
Vol 1	67	63	68	66	750	702
Vol 2	30	39	51	33	816	848
Vol 3	29	30	37	35	816	848
Vol 4	28	33	30	45	507	755
Vol 5	39	42	50	49	549	414
Vol 6	16	18	22	17	516	805
Vol 7	122	138	162	152	-	-

As expected, the quantity of traffic observed flowing through these intersections during peak times is lower than the theoretical maximum values. However, the gap between the simulated and theoretical was quite large. Due to the scenario experiencing flight cancellations, it was initially theorized that the airspace and route structure were saturated which would explain the excessive delay and resulting flight cancellations. However, the traffic flowing through each of these intersections only amounted to approximately 1/10th of the potential quantity. It is, therefore, apparent that capacity constraints are affected by interactions between intersections in series, and modeling them in isolation does not provide sufficient insight to gauge the total system capacity. Another reason for this large difference is the modeling of vertiport timing constraints. In the TIGAR analyses, each operation required 30 sec for takeoff or landing and 30 sec for taxi to or from parking. During this time the vertipad would be unavailable for other operations.

B. System Level Effects

The demand scenarios were simulated using the TIGAR tool and statistics were collected on the average delay imposed on flights, the number of flights that required resolutions to maintain well clear of other traffic, and the number of flights that were canceled due to excessive delay. In the DFW area, the route structure struggled to accommodate all of the demanded traffic. This is apparent from the system level statistics shown in Table 4.

Table 4 DFW System Level Throughput Measured Values

	Small Fleet	Large Fleet	Split Vertiport	Wide Spine
Average Delay [sec]	661	155	473	521
Flights w/ Resolutions	3622	2298	1999	2490
Canceled Flights	3111	400	1789	2128

This study was repeated for the LAX region but with a difference in the way that flight resolutions were handled. Instead of allowing horizontal, vertical, speed, and delay as resolution options, the scheduler was restricted to only utilize departure delay. This setup was used to remove variables from the simulation and highlight the affects of the newly created route structure. The same scenario was simulated for the different route structures as introduced previously. Generally, the LAX airspace was less constrained than DFW. However, without an intentionally designed route structure, the demand was still more than the system could accommodate. With the introduction of a simple system connecting the busiest 10 vertiports, the number of canceled flights decreased sharply. The route structure designed for these same vertiports but in accordance with the guidelines established to maximize capacity had a similar number of flight cancellations but decreased the average delay for all of the flights.

Table 5 LAX System Level Throughput Measured Values

	Straight Routes	Simple Route Structure	Max Capacity Route Structure
Average Delay [sec]	130	651	111
Canceled Flights	1329	316	389

VI. Summary and Conclusions

The results of these analyses show that the individual intersections of a route structure are not as constraining to its performance as previously theorized. While consideration of the angles of intersections are important, more system-wide factors must be examined to enable the proper construction of a high-capacity airspace design. The airspace designs that were examined for this study initially showed an inability to support traffic quantities at the UML-4 level. However, the work contained herein demonstrated that with changes made to reflect the specific demand patterns of the region, the total quantity of operations could be increased. Future work on this topic will seek to better understand the interactions between distinct intersections in the same airspace, as well as suggest ways that better flight scheduling can assist with overall capacity increases. Further development of UAM vehicle technology will enable a better understanding of how vehicles will interact while in close proximity to each other and to vertiports.

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