Airspace Performance Observations of Scalable Autonomous Operations in a High Density Vertiplex Simulation

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Abstract— **The National Aeronautics and Space Administration's (NASA's) High Density Vertiplex (HDV) sub-project aims to develop and demonstrate progressive automation technologies that contribute to the Advanced Air Mobility (AAM) concept. Using Human-and-Hardware-In-The-Loop (HHITL) techniques, HDV demonstrates initial vertiport automation services at vertiports with increased air traffic volume in both simulated and live test environments. In 2023, the Scalable Autonomous Operations (SAO) simulation was conducted in which prototype vertiport, airspace, and ground control station technologies were assessed on technical performance. During the SAO simulation, an observational study captured an initial impression of the HDV airspace performance, potential disruptions to the airspace, and highlighted some capability and procedural gaps. Observations took place in two parts. In the first part, five scenario use cases (Nominal, Missed Approach, Speed Change, Divert, and Multi-Aircraft Divert) were conducted with three human operator roles (Vertiport Manager, Fleet Manager, and Ground Control Station Operator). Researchers collected metrics on throughput, closest point of approach, and airborne delay. In the second part of the study, the Missed Approach scenario was observed under three traffic density levels (20, 40, and 60 operations per hour) to challenge the automation to correctly identify slots in the vertiport arrival schedule. The results showed that the automation successfully found a slot for the Missed Approach vehicle in the 20 operations per hour condition, after some delay it found one in the 40 condition, and it did not find one in the 60 condition. The observations of technical and human performance throughout the five scenario use cases and the Missed Approach case study indicated that for HDV to increase traffic density and maintain or increase throughput, airspace monitoring services should be able to detect and resolve conflicts between aircraft. Furthermore, the roles and responsibilities of human operators need additional definition when it comes to responding to vehicle conflicts.**

Keywords—advanced air mobility, high density vertiplex, urban air mobility

I. INTRODUCTION

Advanced Air Mobility (AAM) is a concept that endeavors to transport people and cargo using electric vertical takeoff and landing (eVTOL) aircraft throughout urban and rural environments. The National Aeronautics and Space Administration (NASA) is currently combining efforts with the Federal Aviation Administration (FAA) and industry partnerships to help realize this goal. In the future, it is projected that the demand for AAM type services such as passenger transportation (i.e. air taxis), or commercial movement of products from warehouses to distribution centers, will increase and become a major industry. Yet, despite proactive investment in this concept, the infrastructure required to support such services is still undefined [1].

It is envisioned that there will be a mixture of automation and human operators that will share responsibility between aircraft, operational planning, and airspace traffic services. Part of the infrastructure that needs to evolve are the takeoff and landing areas called vertiports, which are modeled after traditional heliports [1,2]. Questions remain about how the system architecture will enable high-tempo and scalable operations conducted in urban environments. To support these challenges, NASA's AAM project has funded the High Density Vertiplex (HDV) sub-project which is tasked with developing reference vertiport automation technology and exploring functional allocation between automation and human operators using FAA vertiport design guidance [3].

II. BACKGROUND

A. *Advanced Onboard Automation*

The initial work package that HDV delivered in 2022 was called Advanced Onboard Automation (AOA). The primary goal of AOA was to develop and test a prototype UAM ecosystem using autonomous airspace management, onboard detect and avoid, and contingency management software [4,5]. Human actors shown in Fig. 1 were remote pilots called Ground Control Station Operators (GCSOs), Fleet Managers (FMs), and Vertiport Managers (VMs). Flight operation clearances and strategic deconfliction was controlled by the NASA Provider of Services for UAM (NPSU). The role of the FM was to monitor traffic and operations planning, identify potential conflicts, and develop new flight plans for off-nominal situations using information displayed on the HDV Client FM user interface. The GCSO executed traffic and speed change directives and monitored messages from the FM regarding updates to flight plans by using a combination of the HDV Client GCSO user interface and the Measuring Performance for Autonomy Teaming with Humans (MPATH) ground control station software. The VM monitored traffic, scheduling directives, and managed vertipad status using the HDV Client VM user interface. In addition to advanced systems integration, AOA produced several human factors studies which focused on the human roles, responsibilities, and usability of prototype tools [6,7,8].

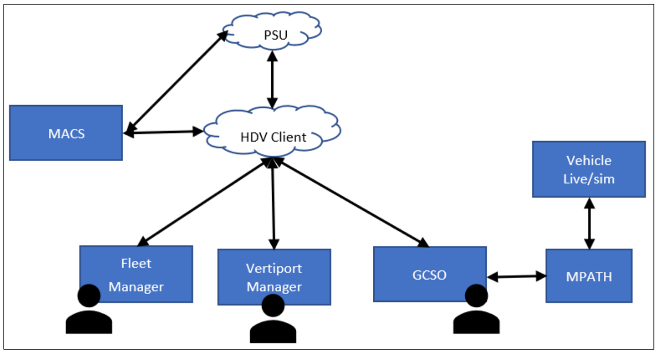

Fig 1. Diagram of AOA human and software configuration

The AOA work package established a platform on which new developments could be integrated and tested. It was designed to be a steppingstone to use cases with greater complexity and increased automation capabilities. The following HDV work package called Scalable Autonomous Operations (SAO) brought vertiport automation much more into focus.

B. *Scalable Autonomous Operations*

a) *Vertiport Automation System:* The HDV SAO work package in 2023 took many of the lessons learned from AOA and expanded on them. One of the biggest additions to the network of airspace services was the Vertiport Automation System (VAS) shown in Fig. 2. The VAS acted as an automated scheduling and sequence manager, handled landing pad allocation, and provided an interface for the NPSU to access vertiport information [9]. More information about the VAS concept can be found in Reference [10].

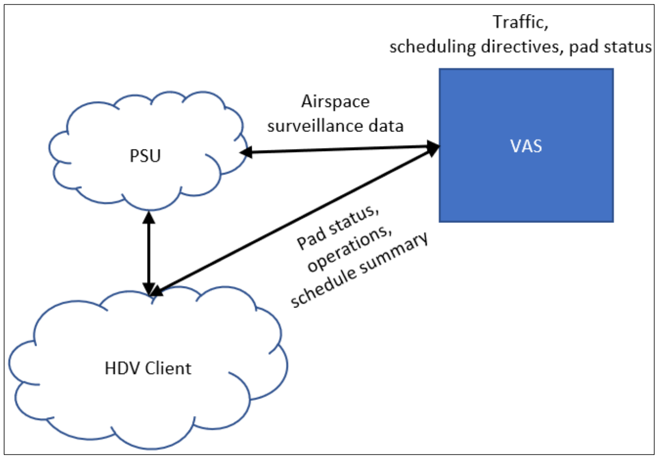

Fig 2. Addition of VAS to the HDV airspace architecture

b) *Increased density and complexity:* The SAO work package introduced increased traffic density and complexity compared to what was previously tested in AOA. Traffic density was increased to 60 operations per hour from 20, and additional use cases were exercised such as Missed Approach, Divert, and Speed Change, all in response to a vertipad being unavailable or a vertiport closure.

Currently, HDV is focused on initial proof-of-concept testing, systems integration, and rapid prototyping of airspace management tools. The tools, procedures, and human operator roles are not yet mature in these early stages. Use cases were intentionally designed to test capability rather than airspace efficiency, however one of the goals of SAO was to capture an initial impression of HDV airspace performance, and to identify potential disruptions to the airspace that could cause impacts to other vehicles. By taking a naturalistic, observational approach, some data was gleaned from the SAO simulated environment that could provide recommendations for the future capabilities and functional allocation within the HDV ecosystem.

C. *Challenges to HDV traffic management*

To assess airspace performance in the classical sense, metrics should be considered that examine the flexibility, predictability, access, and delay of the overall airspace system [11]. The nascent HDV airspace could be considered predictable but inflexible, with little to no room for errors or changes to the original operational intents of the aircraft. Currently, the NPSU is characterized as a strategic deconfliction source because it checks proposed flight plans against airspace resources, then shares operational intent to various listening clients. If that capability functions as advertised, then the operations should work smoothly without further challenges. However, as the vertiport traffic density and complexity increases, one can foresee that the overall operations may stop functioning properly due to periods of demand and capacity imbalance, which may require additional traffic flow management capabilities that have yet to be envisioned. Furthermore, access to the HDV airspace is first-come, first-scheduled and is only limited by the capacity of airspace resources. Yet, in the absence of historical data to define capacity for vertiports, there is no way to evaluate throughput efficiency at this stage.

Finally, delays to operations are a common and concise metric for assessing airspace performance. Typically, delays will come in the form of airborne delay, or ground delay. Currently, the only capability being utilized in the HDV airspace is airborne delay for a single aircraft, i.e., the updated arrival time after an off-nominal procedure such as a Missed Approach or Divert. Delays are not propagated through the airspace when one aircraft goes off-nominal. Hence, the impact to arrival flows of off-nominal procedures performed near the vertiport can be inferred but not yet measured.

Ultimately, assessing the vertiport and airspace performance of a system requires data and associated metrics to measure efficiency. However, the absence of such data in this domain makes such analyses infeasible. The SAO simulation is the first of many HDV studies to come that develop the concept and prototype tools with iterative refinement of capabilities based on an observational set of loosely controlled input conditions. In this paper, the observations of different air traffic events that occurred during the HDV SAO simulation in 2023 will be reported and discussed based on their potential to cause disruptions to the airspace. While the external validity of the scenarios and results are limited due to their highly scripted nature, there is adequate information to provide a snapshot of the current performance of the HDV airspace and provide recommendations to resolve gaps in capabilities and procedures.

III. METHOD

During the SAO simulation, a variety of urban air mobility (UAM) use cases were tested in a virtual and live constructive environment (LVC) using humans-and-hardware-in-the-loop (HHITL) techniques. HDV used small unmanned aerial systems (sUAS) as surrogates for larger unmanned aerial vehicles (UAVs). Live and simulated remotely piloted vehicles were tested at the Langley Research Center (LaRC) flight test range. Virtual traffic was piped into the system by NASA Ames Research Center (ARC) to simulate traffic density at urban air mobility maturity levels (UMLs) 1 – 4 [12].

To complete the SAO simulation, both ARC and LaRC combined their laboratory resources. Extensive systems integration was done prior to the study to ensure that real-time flight and airspace data was synchronously shared between the centers and the live human operators in California and Virginia. The Airspace Operations Laboratory (AOL) at ARC hosted the HDV Client Fleet Manger workstation, the NPSU, and the Multi-Aircraft Control System (MACS). The Remote Operations for Autonomous Missions (ROAM) Unmanned Aerial Systems (UAS) Operations Center [13] at LaRC hosted the HDV Client Ground Control Station Operator and Vertiport Manager workstations, and the VAS.

The SAO simulation ran from two remotely located centers and tested novel system architecture while trying to maintain operational validity. The study design needed to dynamically change as the study progressed to test different functions and adapt to changing situations. Therefore, the results shown should be understood as general trends and observations rather than concrete data.

A. Participants

Three FMs, nine GCSOs and three VMs were recruited to participate in this study. Participants were recruited through the available staff at ARC and LaRC. There were no prerequisites for FM or VM participation. GCSO participants were required to be authorized and trained as small unmanned aerial systems (sUAS) pilots and many had backgrounds in aviation.

B. Scenarios

a) General Traffic: Traffic density consisted of 60 operations per hour at Vertiport 1 with departures and arrivals from 10 different vertiports. There were two types of simulated vehicles used to compose the traffic. The first type (N=60) was MACS generated, and fully automated according to a scripted traffic scenario. The second type (N=3) was Measuring Performance for Autonomy Teaming with Humans (MPATH) generated, which were simulated but also remotely piloted by live GCSOs, and therefore encompassed a mixture of autonomous and manual capabilities. The two types of simulated traffic will herein be called “sim vehicles” and “ownships,” respectively. The aircraft flew cruising altitudes of 325 – 375 feet, with an average speed of 101 knots for sim vehicles and 14 knots for ownships. The length of routes ranged from 23 nautical miles (sim vehicles) to 1.3 nautical miles (ownships).

b) Vertiport 1: During simulation, The CERTAIN range [5] at LaRC was used as the geographical reference for two vertiports (Vertiport 1 and Vertiport 2) and a flight test range. Fig. 3 shows Vertiport 1 had four Touchdown and Liftoff Areas (TLOFs). TLOFs 1 – 3 were used by ownships for departure and arrival, and by sim vehicles for arrival only. TLOF 4 was used by sim vehicles to depart. Vertiport 2 had one TLOF and was used for departure and arrival of ownships only. Fig. 4 shows Vertiport 1 and Vertiport 2 with arrival flows.

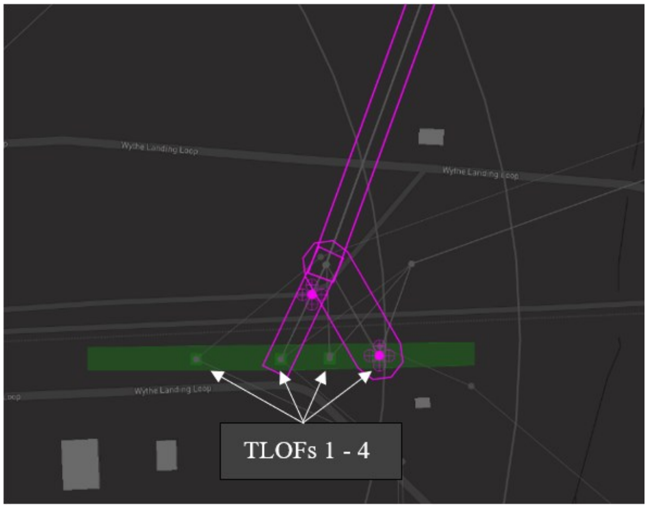

Fig 3. Vertiport Manager HDV Client map view of Vertiport 1

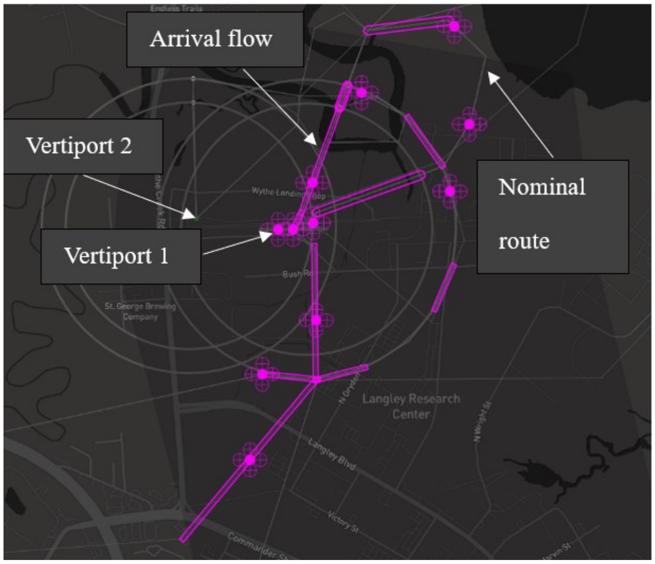

Fig 4. Fleet Manager HDV Client map view of CERTAIN range

Surrounding Vertiport 1 there were five arrival flows coming from the north, west, east, southeast, and southwest. The two flows from the southeast and southwest were also departure flows separated by altitude. There were 12 departures and 53 arrivals in total, including both ownships and sim vehicles. Vertiport 1 schedule capacity was set to 60 operations per hour. The nominal route that ownship vehicles flew was a 1.3 nautical mile loop that both departed and arrived at Vertiport 1. The nominal route took approximately 6 minutes to complete from takeoff to landing. The Vertiport 1 arrival merged four different arrival flows together and was connected to the final leg of the nominal route.

c) *Scenario use cases*

- *Nominal:* Nominal flight demonstrating 60 operations per hour. Three ownship vehicles took off from Vertiport 1, flew the nominal route, then land at Vertiport 1.
- *Missed Approach:* An ownship vehicle executed a Missed Approach holding pattern to give way to an emergency landing ownship.
- *Missed Approach at 20, 40, and 60 operations per hour:* The Missed Approach scenario tested under 20, 40, and 60 operations per hour was added at the end of the study to examine the impact of different traffic levels on the feasibility of the Missed Approach procedure.
- *Speed Change:* Temporary vertiport closure with minor delay (delay < 60 seconds). Two ownship vehicles were impacted.
- *Divert:* Temporary vertiport closure with moderate delay (Delay=3 minutes). Two ownship vehicles were diverted away from Vertiport 1 and landed at Vertiport 2.
- *Multi-Aircraft Divert:* Temporary vertiport closure with major delay (Delay=4 minutes). Three ownship vehicles were impacted. The first executed a missed approach procedure, and then diverted to Vertiport 2. The second diverted to Vertiport 2, and the third slowed down before landing at Vertiport 1.

C. *Tools*

a) *MACS:* The Multi-Aircraft Control System simulation software designed to support human-in-the-loop airspace operations research [14]. In this study, MACS was used to run the simulation platform that injected simulated traffic into the airspace for the ownship vehicles to share the airspace resources.

b) *MPATH:* The Measuring Performance for Autonomy Teaming with Humans ground control station software was used by GCSOs to command and control simulated vehicles [15]. GCSOs interacted with MPATH to upload flight plans, launch vehicles, and execute operation modifications such as speed changes, missed approaches, or diverts.

c) *VAS:* The Vertiport Automation System was responsible for managing the schedule of arrival and departure operations at the vertiport. It reserved slots for arrivals and departures based on operation requests received from the HDV Client. Additionally, the VAS granted landing clearances when it received landing requests from the HDV Client at the Initial Approach Fix (IAF) and Final Approach Fix (FAF) of Vertiport 1. The Vertiport Manager also has the capability to utilize the VAS to either close the entire vertiport or a specific TLOF [10].

d) *NASA Provider of Services for UAS (NPSU):* The NPSU provided clearances for submitted operations by analyzing operational intents against vertiport resource availability and previously approved operations. This provided a base layer of strategic deconfliction because the NPSU only approved an operation if it determined there was existing capacity at the target resource. The NPSU also distributed notifications about operational states such as "approved," "activated," or "closed."

e) HDV Client: The HDV Client provided a user interface through which operators could track trajectory and flight state of vehicles. The HDV Client supported three operator modes, the Fleet Manager, the Vertiport Manager, and the Ground Control Station Operator. The HDV Client also integrated with other systems like the VAS, MPATH, the NSPU, and MACS. By subscribing to data shared by these systems the HDV Client served as the central user interface for shared situation awareness across all human operators [7]. Operators tracked vehicle positions, operation state such as "activated," status updates such as "cleared to land," or notifications such as "required replan." HDV Client also integrated all traffic types, both sim vehicles and ownships, into a single situation display.

D. *Procedure*

Participants came to the labs at ARC and LaRC for a briefing before data collection where they were introduced to their flight management tools, workstations, and scenario tasks. Participants then completed brief demographic questionnaires.

At the beginning of every scenario, the Sim Director assigned takeoff times to each GCSO. Each GCSO used voice communication to request their takeoff times from the FM. The FM responded to each GCSO and scheduled their flight plan in the HDV Client. After all GCSOs had their takeoff times reserved, MACS simulated background traffic was started. Once traffic started, the FM, GCSOs, and VM performed their scenario tasks.

To ensure that ownships did not encounter any conflicts with sim vehicles that would distract them from performing their scenario tasks, one researcher needed to visually monitor the airspace and delete any sim vehicles that looked like they were coming into conflict. There were no formal criteria for vehicle deletions, it was determined simply by subjective observation.

After each scenario, participants completed human factors questionnaires. After the completion of runs, participants engaged in an informal interview process, where researchers asked unstructured questions about their overall experience during the different scenarios.

IV. RESULTS

The purpose of this study was to gain an initial impression through observation of the current state of HDV airspace performance. By analyzing throughput, amount of airborne delay for ownships, number of spacing violations, and the performance of the Missed Approach scenario use case at different levels of traffic (20, 40, and 60 operations per hour), a preliminary snapshot emerged. Discussions of the findings from this study will be used to identify gaps in capability or procedures, and recommendations for resolving gaps.

A. *Throughput*

To evaluate whether each use case scenario was performed in the environment of 60 operations per hour, the Vertiport 1 throughput over one hour was calculated. The data confirmed that during the elapsed time of 60 minutes there were a total of 60 operations creating constant demand on Vertiport 1 at a rate of one operation per minute. This confirms the traffic scenario used for SAO Sim met the criteria for density as described by the initial sub-project criteria. For this study, Vertiport 1 capacity was scripted to accommodate up to 60 movements (takeoff and landings) per hour. In the future, it will be necessary to more rigorously establish capacity criteria to evaluate whether the demand is balanced with the capacity at TLOFs, vertiports, and arrival waypoints.

B. *Spacing violations*

Human operators were only involved in the HHITL environment to respond predictably rather than dynamically to highly scripted scenarios. GCSOs were expected to perform and react to scenario tasks as naturally as possible given their sUAS pilot training, but researchers also wanted to avoid any unscripted distractions that would impact the way GCSOs performed. Additionaly, HDV did yet not have tactical resolutions in place for handling aircraft in conflict, and it was intended that vehicles would perform off nominal procedures without affecting any additional traffic in the scenario. Therefore, it was decided that any conflicts percieved through visual observation during the active portion of the scenario between ownship and sim vehicle operations should be deleted.

a) Vehicle deletions: The number of deleted aircraft was recorded to serve as an indicator of how often an operator would potentially have to react to vehicle conflicts. Table 1 shows the average number of deleted aircraft across all runs was 1.6 with a Range of 0 - 6, and 2 vehicle deletions being the most common per run (Mode=2).

Table 1. Number of deleted aircraft across all runs

Descriptive	**Number**
Average	1.6
Mode	2
Max	6
Min	0

Given 60 operations per hour at Vertiport 1, either the FM or the GCSOs would have needed to respond to sim vehicle incursions approximately 1.6 times throughout each scenario.

b) *Closest Point of Approach:* In addition to capturing the frequency of ownship to sim vehicle conflicts, we wanted to describe the frequency and nature of sim vehicle to sim vehicle conflicts. In the case of the latter, sim vehicles were automated and uncontrolled throughout the runs, so all unacceptable Closest Point of Approaches (CPAs) were accounted for. The CPA is the closest distance, both vertically and horizontally, between two aircraft for an entire run. The onboard detect and avoid automation Flarm [16], which was integrated with the HDV ground control station, defines the well-clear boundaries as 500 feet horizontal and 100 feet vertical.

Table 2 shows the average number of times per run that two sim vehicles had a CPA that exceeded the well-clear boundaries (Mean=14.4), the average horizontal (Mean=110.23 feet) and vertical (Mean=57.64 feet) distances between the close vehicles, and the range of distances in feet horizontally (Min=42.33, Max=300.2) and vertically (Min=40.42, Max=61.64)

Table 2. Closest Point of Approach less than 100 feet vertical and 500 feet horizontal

Descriptive	Number
Average number of CPAs	14.4
Average horizontal distance	110.23
Max	300.20
Min	42.33
Average vertical distance	57.64
Max	61.54
Min	40.42

Unlike the case with ownship to sim vehicle deletions, sim vehicles which are automated by MACS were allowed to fly their courses uninterrupted, and largely unobserved during the run. Post-study analysis of the logs revealed that there were, in fact, several instances of CPAs exceeding the well-clear boundaries that none of the airspace systems had any way of alerting the operators to. For example, the NPSU coupled with the VAS strategically deconflicted departure and arrival times, yet enroute segments of operations in conflict were left unaccounted for. The HDV Client also does not monitor for vehicle conflicts, which was what necessitated the ad hoc deletion of vehicles and allowed unacceptable sim vehicle CPAs to go undetected.

C. Delay

Three scenario use cases in the simulation gave an initial glimpse of delay absorption capabilities that have been developed by HDV so far. The Missed Approach scenario used a holding pattern near the vertiport arrival stream, the Divert scenario redirected ownships to Vertiport 2, and the Multi-Aircraft Divert contained both Missed Approach and Divert procedures. In these scenarios, the results of ownships performing off-nominal procedures represented the first look at events in the airspace that could propagate delay throughout the system.

To observe the amount of airborne delay that ownship vehicles incurred during all Missed Approach and Divert procedures, the original scheduled time of arrival was compared to the new scheduled time of arrival (Table 3). The average delay of the Missed Approach procedure was 2.5 minutes (SD=1.2 minutes), and the average delay of the Divert procedure was 1.3 minutes (SD=1.1 minutes).

Table 3. Airborne delay (minutes) by condition

Descriptive	Missed Approach	Divert
Average	2.5	1.3
Max	4	4
Min	1	0
SD	1.2	1.1

It was not possible at 60 operations per hour without deleting some vehicles from the simulation to make room for the merging ownships. With vehicle deletions, overall airspace system delay was kept at a minimum, restricted to only ownship vehicles with changes to their arrival times. Had sim vehicles been allowed to fly their original course with no deletions, the FM would not have been capable of conditioning the traffic with the current set of capabilities afforded by the HDV Client.

Although the criteria for in-flight vehicle deletion was subjective, it was clear that the airspace management systems (NPSU, VAS, and HDV Client) were not attuned to alerting operators about potential conflicts. The proper detection and resolution of these conflicts would have resulted in greater congestion and airborne and/or departure delays affecting a larger subset of the traffic.

D. Missed approach at 20, 40, and 60 operations per hour

After observing the interactions between the scripted scenario procedures and the actual outcomes of the scenarios, one scenario use case became of particular interest. The Missed Approach procedure was run 11 times over the course of data collection and failed 3 times. A “failed” Missed Approach scenario was indicated by the FM’s inability to generate an approach route once the ownship was already flying the Missed Approach procedure holding pattern. Generating the approach route was predicated on the VAS and NPSU providing a landing clearance based on available capacity at the vertipad. Given no other alternatives, if the ownship could not be cleared due to overdemand of the vertipad, then the scenario failed.

In addition to some runs failing, there were also successful runs that experienced a longer than expected time to generate the approach for ownship. In Table 4 this is referred to as "interface delay," or the amount of time greater than zero that it took for the FM to generate an approach route to submit. Out of 8 successful runs, it took the FM an average of 40 seconds to generate an approach route and arrival time back to the vertiport. Out of 3 unsuccessful attempts, it took the FM an average of 1 minute and 48 seconds to generate the approach.

Table 4. Frequency and duration of interface delay on successful and failed Missed Approach procedures

Descriptive	**Number**
Number of successful Missed Approaches	8
Number of failed Missed Approaches	3
	(minute:seconds)
Average time to generate route (success)	0:40
Min	0
Max	3:05
Average time out (fail)	1:48
Min	0:15
Max	3:40

It was determined that the "generate approach" algorithm only looked for an open timeslot at the same vertipad that ownship was originally landing on, without looking for alternate available vertipads. The discovery led to a post hoc case study which attempted to show the performance of the Missed Approach procedure at different traffic levels. The results from this case study (Table 5) showed at 20 operations per hour the Missed Approach procedure worked on the first try. At 40 operations per hour, the Missed Approach procedure worked but there was 3 minutes and 5 seconds of interface delay, meaning it took the FM longer than expected to generate an approach route. At 60 operations per hour, the algorithm failed to find an approach route and the operation timed out after 3 minutes and 16 seconds.

Table 5. Missed approach at different traffic levels

Traffic Level	**Original STA**	**Invoke Missed Approach**		**New STA**	**Interface Delay (mins)**
		First attempt	*Final attempt*		
20	12:26	12:25	--	12:29	0:00
40	10:31	10:24	10:27	10:31	3:05
60	11:16	11:16	11:19	--	3:16

As expected, it was easier to find an open arrival time slot at the lower traffic level, and it got increasingly harder as the traffic level increased. These results offer a glimpse of the potential impact to vertiport operations as capacity is reduced and offers an approximation of the traffic density at around which time these disruptions may start to occur. The implication from this case study is at a certain threshold of density, either strategic or tactical demand and capacity balancing interventions should be used.

V. DISCUSSION

A. Throughput and demand/capacity balancing cannot accurately be assessed without capacity values

As HDV looks to increase throughput over time, it will be necessary to understand the capacity limitations on certain airspace resources such as TLOFs, vertiports, and arrival flows. Factors that influence capacity limitations are loading/unloading, and taxi time of vehicles, crew resource management, wind speeds, vertiport infrastructure, and more. Eventually, temporary reductions in capacity can throw a vertiport into a state of over-demand. A classic example is weather either impacting or temporarily shutting down a high demand airspace resource. Procedures will need to already be in place to handle the imbalance.

B. Procedures and responsibility allocation for strategic and tactical traffic conditioning should be considered

The ripple effect of delay by vehicles merging and spacing with traffic on the arrival flow was intentionally edited out of the scenarios by deleting vehicles that could have interfered with the ownships, and by leaving sim vehicles uncontrolled. However, receiving airborne delay under near optimal circumstances with no other impacts to traffic flows is unlikely during high-tempo operations. Due to the amount of vehicle deletions that had to take place to prevent conflicts, it was clear that an operational procedure should be in place to manage the conflicts. Furthermore, there is currently no way to assign strategic ground delay, which will be necessary during periods of demand/capacity imbalance. Examples from traditional airspace operations are the various types of Traffic Management Initiatives (TMIs) which are currently used by the FAA to manage fluctuating and variable demand and capacity in the National Airspace (NAS). Similarly, high-density UAM Airspace resource efficiency and throughput will be at a premium, so a future direction for HDV to explore could include considerations for how to strategically as well as tactically condition traffic.

C. Conflict detection should be improved and responsibility should be allocated

In 2021, the HDV AOA simulation and flight test investigated both low- and high-conflict scenario use cases with autonomous onboard detect and avoid services [6]. Independent Configurable Architecture for the Reliable Operations of UAS (ICAROUS) [17] demonstrated acceptable results and performance, meaning vehicle to vehicle conflicts were detected and automation took over the aircraft to plot a new route that avoided conflict. However, currently ICAROUS is not integrated with HDV Client, so a GCSO would have awareness of conflicts that the FM would not. This reduces shared situation awareness between collaborative operator roles. Questions remain such as:

- With who or what system should the responsibility lie for monitoring and detecting conflicts?
- With who or what system should the responsibility lie for taking action to avoid conflicts?

As the results from the HDV SAO simulation indicate, there will be a future need for a monitoring algorithm that both detects and alerts the listening systems to all vehicle conflicts, as well as operational procedures for mitigating conflict.

D. Crawl, walk, run

It should be noted that that the gaps in capabilities and procedures discussed in this paper were previously known to be outside the scope of the SAO simulation. Because HDV is developing and integrating a completely novel system architecture, there will noticeably be some trade-offs to ecological validity in the beginning, as the foundation needs to be laid first before more complex issues can be studied. The project has adopted the “crawl, walk, run” philosophy which is a staged approach to product development. Easier scenarios that focus more on system integration and proof of concept will take place earlier on, with increasing levels of complexity and automation as the project reaches later stages. The discussion of SAO simulation airspace performance analysis is meant to provide awareness, recommendations, and research questions that could be applied to future iterations of the HDV ecosystem.

VI. CONCLUSION

The SAO simulation confirmed the HDV airspace could perform nominal and off-nominal use case scenarios during 60 operations per hour using a reference vertiport automation system. Vertiport capacity was assumed to match the expected traffic demand. To preserve a safe and distraction free operational environment, vehicle conflicts were either removed from the system or ignored. However, performing the off-nominal Missed Approach procedure at increasing levels of traffic indicated that enhanced capability to merge and space vehicles will be necessary in the future. It is recommended that HDV explores scenario use cases where operators can tactically condition traffic and experience widespread delay impacts across multiple vehicles.

Looking ahead, in addition to advancing operator tools and capabilities, HDV will begin studying the Vertiplex Operations (VO) work package, which will connect airspace management services and vertiport automation services to support a multiple vertiport network. VO will expand the number of VMs, FMs, and GCSOs, and rely heavily on automation to demonstrate contingency management use cases during dense operations.

VII. ACKNOWLEDGEMENTS

The HDV research team would like to acknowledge the laboratory personnel involved with the SAO simulation. Many individuals, both scientific and technical, contributed continuous support throughout the mission, including the Airspace Operations Laboratory (Ames), the Autonomous Vehicle Applications Laboratory (Ames), and the Remote Operations for Autonomous Missions (LaRC).

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