Estimating Airspace Resource Capacity for Advanced Air Mobility Operations

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Demand capacity balancing (DCB) has been proposed as a strategic mechanism to balance efficiency and predictability for Urban Air Mobility (UAM) operations when operational uncertainties are high. In this paper we seek to determine how DCB can be implemented to ensure safe and efficient UAM operations in coordination with a tactical deconfliction system. We use simulations to explore the safety of representative UAM operations applying tactical deconfliction methods, and estimate airspace resource capacities that could be applied, using DCB, to ensure safe and efficient UAM operations. We apply this approach to determine airspace capacity in two baseline route structures - simulating merging flows and crossing flows respectively - which are then applied to a hypothetical UAM network in New York City. The benefits of DCB to support tactical deconfliction for safety assurance across a range of demand values is demonstrated and compared to safety metrics applying tactical deconfliction only, and to a baseline without DCB or tactical deconfliction. In addition, we also show the trade-off between ground delay and safety metrics while implementing various levels of DCB. The results suggest that DCB may be a feasible mechanism to ensure safe and efficient UAM operations. The results also reveal some early insights into interactions between the strategic DCB and the tactical deconfliction.

I. Nomenclature

С	=	DCB capacity in each time window
S	=	DCB window size (time interval)
Test	=	estimated time to check point
D_{gs}	=	ground-separation distance
D_{nmac}	=	NMAC radius
D_{los}	=	LOS radius
D_{ls}	=	low-separation-warning distance
D_{hs}	=	high-separation distance
V	=	lower bound of the aircraft speed
δ	=	aircraft acceleration/deceleration
β	=	mean value of departure interval from a vertiport
$d_{(k-1)o}$	=	distance between the preceding aircraft $k - 1$ and the departure vertiport of the current aircraft k
d_{lf}	=	distance between the following and leading aircraft
$T^{\check{K}}_{\Lambda}$	=	actual departure time list
T_{S}^{K}	=	scheduled departure time list

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II. Introduction

B ASED on forecasts, there will be significant growth in the number of air vehicles operating in urban environments over the next 20 years [1–3]. One key component of this traffic is electric vertical take-off and landing (eVTOL) cargo and passenger air taxis to support Urban Air Mobility (UAM). Existing Air Traffic Management procedures for managing urban air traffic, which is primarily helicopters and general aviation aircraft today, are not expected to scale sufficiently to support the number of these operations forecast, as demonstrated by human-in-the-loop simulations carried out by NASA [4]. For these reasons, new approaches to managing urban air traffic beyond what is currently available through traditional air traffic control (ATC) are required. NASA and the FAA propose that concepts from UAS traffic Management (UTM) [5] may also be appropriate for UAM [6, 7].

In many of the architectures proposed for UTM, strategic deconfliction – resolving a predicted conflict prior to departure or well upstream of it – is proposed to ensure separation provision [8–13]. Strategic deconfliction is also a key function in the FAA concept of operation for UAM [7]. However, air taxi operations particularly may see different operational uncertainties to those of smaller UAS, which may degrade the effectiveness of strategic deconfliction for this use case. Departure uncertainty increases with the need to deplane and enplane passengers, while other turnaround functions required for UAM, such as battery changes, may also introduce uncertainty. Fleet rebalancing needs in UAM may also be significant [14], potentially adding further operational uncertainty. Uncertainty in airborne flight times may be impacted by micro-weather in and around urban areas, some of which is less well understood than weather impacting traditional aircraft. In addition, the airborne flight times may be further changed once the tactical deconfliction is activated. How these operational uncertainties are to be accommodated in UAM operations is still under discussion. Accommodating them with strategic deconfliction may lead to conservative operational intent definitions, such as large operational intent volumes [15]. Overly conservative sizing of operational intent volumes could reduce efficiency [16]. Alternatively, if these uncertainties are not suitably accounted for in the definition of operational intent for strategic deconfliction, frequent replanning may be required, which could reduce predictability and may result in significant delays when operations must be replanned into an already congested schedule [16].

Demand capacity balancing (DCB) is specifically called out by the FAA as potentially required to support UAM operations as the number of operations increases [7] and may provide a tool to balance efficiency and predictability when operational uncertainties are high. Here, DCB refers to a mechanism that strategically defines airspace capacity and manages demand - appropriately aggregated - for constrained resources in such a way as to prevent demand from exceeding resource capacity. Typically, it does not include explicit strategic deconfliction, but leaves deconfliction and separation assurance to tactical functions (by the pilots, air traffic controllers and their decision support tools in traditional ATM). The need for DCB is driven by the existence of resources that are capacity constrained. Such resources are defined in traditional aviation (runways, sectors, metering fixes etc.), but UAM operations may be constrained in different ways. Resource capacities may be constrained in UAM for a number of reasons, including to ensure the effectiveness of separation assurance methods used tactically; to manage physical infrastructure constraints (such as for vertiports or communications spectrum); to reduce environmental impact (particularly noise); and in contingency management. Each of these applications is discussed below.

Analogous to the use of sector capacities to ensure that traffic densities are suitably low that air traffic controllers can safely provide separation assurance, DCB can be used in UAM to increase safety and mitigate potential air traffic congestion. This involves reducing demand to levels at which separation assurance tools that provide tactical deconfliction and detect-and-avoid functionality reduce the probability of encounters to acceptable levels and enable more predictable traffic.

Because of their size and the use case to support passengers, UAM vehicles are expected to pose significant requirements on landing and take-off ports (vertiports). These are likely to be significantly capacity constrained because of their expected location in urban areas. The safety case for UAM may also necessitate significant data flow through the communications infrastructure. Depending on the communications technology used, saturation of communications spectrum is possible [17] and could lead to loss of data, which would increase communications latency as systems rebroadcast. Constraints on communication spectrum use may therefore be required to meet the UAM safety case, although this is highly dependent on the communications technology used.

While the electric propulsion technology being developed for UAM vehicles has different noise properties to existing helicopters and fixed-wing aircraft, traffic densities forecast for UAM are significantly higher than current urban helicopter and fixed-wing operations. Constraints on noise are therefore expected [3, 8, 18]. These may, however, be in the form of noise thresholds. This may mean that noise-based demand capacity balancing takes the form of a comparison between dynamic cumulative noise maps and noise threshold maps. Other environmental constraints may also be imposed, such as to prevent visual pollution.

Because of the use case to support passengers, management of contingency operations, especially in emergencies, will need to meet strict safety requirements. This may include ensuring that emergency landing zones are available to vehicles at all times during operations. Constraints may also be required to safely accommodate mass contingency events, including ensuring emergency landing zone availability, and preventing the overloading of any required involvement from ATC.

In this paper we focus on the first application for DCB - ensuring the effectiveness of separation assurance tools, e.g. a rule-based tactical deconfliction function in this paper. We use simulation to explore the effectiveness of appropriate resource and capacity definitions for UAM and identify quantitative approaches to estimating those capacities, under a given tactical deconfliction tool. We apply these approaches to determine resource capacities for a hypothetical UAM network serving a dense urban region, and validate that the resource and capacity definitions are suitable to ensure safe and efficient UAM operations, together with a tactical deconfliction function. Resource and capacity definition for the other DCB use cases listed above is left for future work.

Section III provides background information and describes relevant work from the literature. This is followed by the research objectives in Section IV and our experimental approach is Section V. Results are presented in Section VI, which is followed by conclusions and recommendations in Section VII.

III. Background

In traditional Air Traffic Management (ATM), separation assurance or conflict resolution is provided by air traffic controllers in each sector. Safe separation is typically achieved by tactically delaying aircraft through vectoring or speed control. However, when traffic densities are high, either because of high demand or reduced airspace capacity, e.g., due to convective weather, to ensure safe separation, controllers may need to propagate these airborne delays upstream. Without strategic intervention, airborne holding may be required, which is undesirable both from an operating cost perspective, and because it can block off significant airspace, impacting other traffic. For this reason, when imbalances between traffic demand and airspace capacity are forecast, strategic demand capacity balancing initiatives (called Traffic Management Initiatives in the U.S.) are typically applied to reduce demand on resources to levels that do not require excessive tactical airborne delay for separation assurance. These initiatives effectively space traffic out so that it can be separated tactically without the need for excessive delay through e.g., airborne holding. In the U.S., a number of strategic demand capacity balancing initiatives are used by the FAA. These include ground delay programs, ground stops and airspace flow programs, which delay aircraft on the ground before take-off; airborne reroutes, which route aircraft around congested airspace; and the Collaborative Trajectory Options Program (CTOP), which provides flight operators with the flexibility to submit route alternatives and avoid ground delays. [19]

Scheduling and flight planning in UAM operations have been studied widely in recent years. Approaches have been proposed for terminal area scheduling that accounts for UAM constraints [20], and for managing dense traffic flows in unstructured airspace [21]. A vertiport scheduling algorithm has also been used to compare vertiport capacity and throughput under different vertiport configurations [22].

Ref. [14] estimated capacity and throughput for a given set of parameters that represent an operational UAM ecosystem. Using a macroscopic scenario simulator, the authors estimated the impact of the underlying infrastructure and traffic management system on throughput.

Ref. [16] quantified the effectiveness of strategic deconfliction in mitigating operational uncertainty in the form of normally distributed departure and airborne errors. The results suggest that departure and airborne delays under strategic deconfliction are highly sensitive to how much rescheduling is required into the existing schedule. Depending on how rescheduling is accommodated, strategic deconfliction may result in impractically high delays even in early-stage UAM operations. The effectiveness of DCB in mitigating operational uncertainty was not evaluated in that work because of the difficulty in defining resource capacities. The work in the present paper seeks to resolve this difficulty. In related work, a separation and resolution study by NASA [23] found that using a combination of strategic scheduling, tactical scheduling at crossings, speed control near crossing points, and separation management leads to a system that is insensitive to trajectory prediction errors while maintaining high network-throughput and flexibility.

The capacity of existing and modified helicopter routes and procedures (including separation assurance by air traffic controllers) to support UAM operations has been explored through human-in-the-loop experiments by NASA [24]. In that work, three different levels of UAM traffic in the Dallas-Fort Worth (DFW) area were evaluated, with the number of operations that could be managed by air traffic controllers recorded in each case across a series of experiments. That work identified that the self-reported workload at busy airport towers could not be effectively managed at the forecast UAM traffic levels, even with the modified routes and procedures, so other approaches for UAM traffic management -

such as proposed in [7] - will be needed.

One approach to increase the capacity of airspace to support UAM operations is the use of algorithms for tactical deconfliction that provide conflict resolution actions to maintain separation. One such example is the NASA Autoresolver algorithm [25, 26], which was originally developed to support traditional air traffic control, but has been modified to provide separation between UAM aircraft [27]. Another example is a deep-reinforcement learning (DRL) tool [28] that provides speed change advisories to maintain separation. The approach utilizes Proximal Policy Optimization (PPO), modified to incorporate an attention network. This allows the agent to have access to variable aircraft information in the airspace resource to achieve high traffic throughput. The algorithm is trained using a centralized learning, decentralized execution scheme. Numerical results show the proposed framework significantly reduces offline training time, increases safety performance, and suggests much less frequent maneuver advisories than is typical for human controllers.

In order to improve the safety of the learning-based separation assurance tool in unseen environments with uncertainties, a safety module [29] was added to the DRL based separation assurance tool described above. [28] The module directly addresses both model uncertainty and state uncertainty to improve safety. It consists of two sub-modules: (1) a state safety sub-module is based on the execution-time data augmentation method to introduce state disturbances in the model input state; and (2) a model safety sub-module is a Monte-Carlo dropout extension that learns the posterior distribution of the DRL model policy. Extensive numerical experiments showed that the sub-safety modules help the DRL agent significantly improve its safety performance in an autonomous separation assurance task. [29]

In this paper we seek to determine how DCB can best be implemented to ensure the safety and efficiency of UAM operations supported by tactical deconfliction algorithms, such as those described above, and to quantify the effectiveness of DCB in managing UAM demand safely and efficiently under operational uncertainty.

IV. Objectives

The objectives of this research are twofold:

- 1) Design and demonstrate a simulation-based approach to quantify the capacity of critical resources in UAM airspace to assure safety by tactical systems. This becomes a search problem that identifies the traffic level at which safety can no longer be assured by the tactical systems.
- Validate the effectiveness of strategic DCB to manage demand under operational uncertainty in such a way as to assure safety and efficiency of the tactical systems. This is done by calculating safety and efficiency metrics, and comparing them to scenarios that do not apply DCB.

V. Approach

Previous work has applied Monte Carlo methods in fast-time simulation to evaluate the safety case for UTM [30]. This approach allows statistics to be calculated quantifying the probability of a Mid Air Collision (MAC) under different operational conditions and assumptions. A similar approach is used to evaluate the safety and efficiency of UAM operations in two types of baseline traffic scenarios and a hypothetical airspace in New York City with en route corridors and approach/departure routes based on existing helicopter routes.

Three metrics are used to evaluate safety and efficiency of the simulated UAM operations:

- 1) The cumulative duration of loss of separation (LOS) events, with LOS defined by a distance of 100m;
- 2) The cumulative duration of near mid-air collision (NMAC) events, with an NMAC defined by a distance of 5m; and
- 3) Average ground delay.

The simulation tool and setup for collecting and calculating these safety and efficiency metrics are described in Section V.A below, followed by a description of the tactical deconfliction algorithm used for separation assurance in Section V.B, and the DCB algorithm applied to precondition traffic strategically in Section V.C. This is followed by a description of how the simulation results are used to estimate resource capacities, and to identify the most efficient DCB implementation in terms of flight ground delay in Section V.D.

A. Simulation Setup

As in Ref. [30], Monte Carlo methods were used to generate a distribution of vehicle separations, based on simulation runs that generate demand stochastically (in time and space), according to an input parameter defining aggregate demand. In Ref. [30], thousands of simulations were run to generate vehicle separation profiles in each scenario, and a similar approach was employed here. Because of the length of time required to run a single simulation,

in this work results at each combination of parameter settings were aggregated over 30 simulation runs, resulting in a total of 25,920 simulations across all scenarios. Safety metrics (LOS and NMAC) were collected and calculated from vehicle separations, while efficiency metrics (ground delay) were calculated from the planned and actual departure time.

Each simulation run contains a fixed number of operations on each route. The departure time interval I_j between simulated flights (without DCB) T_S^k is sampled from an exponential distribution with the expectation defined by the traffic density β :

$$I_j \sim Exp(\beta)$$
$$T_S^k = \sum_{j=1}^{k-1} I_j$$

Based on queuing theory, the distribution of departure intervals will then follow the Poisson distribution, where

$$N \sim Pois(\frac{1}{\beta})$$

For each simulated flight, initial aircraft cruise speed is sampled from a uniform distribution derived from the range of cruise speeds specified for eVTOL aircraft under development around the world, where

$$v_i^k \sim \text{Unif}\{30, 31, 32, 33, 34\}(m/s)$$

Based on the simulated flight departure times, randomly sampled aircraft speeds, and the route on which the aircraft is to fly, 4-dimensional trajectories are generated and simulated using the BlueSky [31] simulator. The BlueSky simulator is capable of running a large number of aircraft simulations in parallel efficiently. In addition, it is highly configurable, e.g., allowing configuration of vertiport locations, waypoint locations, UAM routes, and aircraft performance parameters.

BlueSky uses TrafScript as a language to describe flight plans and simulate aircraft movements. The flight plan includes three parts: (1) flight information, including aircraft model, cruising speed and altitude; (2) origin and destination vertiports; and (3) all the waypoints along the flight mission. In addition to following a flight plan, BlueSky allows for commands to be given to aircraft to change the flight trajectory or speed dynamically during a simulation. We use external code to interact with the simulation at each time step, modifying departure time to implement strategic ground delay based on DCB, as well as aircraft speed to implement the tactical deconfliction algorithm.

Algorithm 1 describes how operations are tactically deconflicted to maintain separation. At the beginning of the simulation, we generate a list of initial departure times T_S^k for K aircraft on each route. All DCB time windows at defined resources (such as merging points or crossing points) are initialized with an empty projected demand list. The flight k will not be clear for take-off until all of the following requirements are satisfied:

- 1) Departure time check: simulation time t equals flight k actual departure time T_A^k ;
- 2) Ground tactical separation check: distance between the preceding departure aircraft (the flight that just left the same vertiport) and the origin vertiport is greater than ground separation assurance distance D_{gs} ;
- 3) DCB separation check: the projected traffic demand in corresponding DCB window $WINDOW(t + T_{est})$ is less than or equal to the DCB capacity C set to this time window of this resource.

If flight k is clear for take-off and released successfully at time t, the corresponding DCB window $WINDOW(t+T_{est})$ is reserved for this flight (T_{est} is the en route time from the origin vertiport to this resource), while if operation k does not satisfy the ground tactical separation check or the DCB separation check, the actual departure time T_A^k increases by one second (system simulation unit time), which corresponds to a one-second ground delay.

Once simulated aircraft are airborne, a decentralized airborne tactical deconfliction algorithm is applied to every flight in an attempt to maintain safe separation. This is described in Section V.B below.

To study and evaluate how DCB can be used to precondition traffic for tactical deconfliction for the most typical flow patterns in structured airspace, we define two baseline route scenarios as shown in Figure 1. Scenario 1 simulates crossing flows, with two independent flight routes crossing at an intersection point. Scenario 2 simulates merging traffic, with two flows from different origins merging together at the single point, and continuing as a single flow.

After identifying the DCB capacity values that enable effective tactical deconfliction for the baseline cases described above, we apply these capacities in a more complex scenario involving multiple capacity constrained resources. This allows us to evaluate the effectiveness of DCB to support safe operations in a more realistic scenario. The region simulated is New York City (NYC), which has a well defined network of helicopter routes and heliports, and is likely to be capacity constrained under future UAM operations. Helipad and route data was collected from the public NYC helicopter route chart [32]. This was used as the basis for a UAM corridor network for NYC in BlueSky, as shown in

Algorithm 1: Integration of DCB and a rule-based tactical deconfliction

1 Generate scheduled departure time list T_S^K for *K* aircraft 2 Copy $T_A^K \leftarrow T_S^K$ as the actual departure time 3 Generate an empty DCB window list WINDOW 4 for $t \leftarrow 1$ to T do BlueSky.step(); 5 // Ground and DCB separation check: 6 if $t == T_A^k$ then 7 Compute distance between the preceding aircraft k - 1 and the origin vertiport $d_{(k-1)o}$ 8 if $d_{(k-1)o} \ge D_{gs}$ and WINDOW $(t + T_{est}) \le C$ then 9 Release aircraft k 10 WINDOW $(t + T_{est}) + = 1$ 11 else 12 $\int T_A^k + = 1$ 13 // In-air tactical mitigation: 14 foreach pair of aircraft do 15 Identify the leading aircraft AC_l and following aircraft AC_f 16 Compute the distance d_{lf} 17 if $d_{lf} \leq D_{nmac}$ then 18 $v_f \leftarrow \underline{V}$ NMAC + = 119 20 else if $d_{lf} \leq D_{los}$ then 21 $v_f \leftarrow \underline{\mathbf{V}}$ 22 LOS+=123 else if $d_{lf} \leq D_{ls}$ then $\downarrow v_f \leftarrow v_f - \delta$ 24 25 else if $d_{lf} \ge D_{hs}$ then $\downarrow v_f \leftarrow v_f + \delta$ 26 27 **28** Compute average ground delay: GroundDelay $\leftarrow \text{mean}(T_A^K - T_S^K)$

29 return (GroundDelay, LOS, NMAC)



(a) Scenario 1: crossing flow

(b) Scenario 2: merging flow

Fig. 1 Baseline routing scenarios and structures.

Figure 2. There are 12 vertiports for landing and taking off, 11 flight routes, and 114 defined waypoints. To simplify the problem, we simulate operations on only a subset of this network with traffic from 3 vertiports interacting at a single crossing point and a single merge point, shown in Figure 3. This adds realism relative to the baseline routing scenarios, and explores the effectiveness of DCB applied to multiple resources.



Fig. 2 Flight routes in the NYC region are built into BlueSky from the public helicopter route chart [32].

B. The Tactical Deconfliction Capability in Simulation

The capacity of a resource, defining the amount of traffic that can safely be accommodated at the resource, is closely tied to the tactical deconfliction capability in place to separate aircraft, and different tactical deconfliction capabilities will yield different resource capacity values. In this paper we intentionally implement a simple rule-based tactical deconfliction algorithms, as the focus of the paper is on exploring how DCB can be used to precondition traffic so that it can be accommodated safely by the tactical deconfliction systems in place. Two forms of tactical deconfliction are applied in this paper. The first one deconflicts operations on the ground, for departure separation assurance, while



Fig. 3 Experiment 3 test scenario representing a simplified NYC UAM network.

the second one deconflicts operations in the air, for airborne separation assurance. These two algorithms are simple rule-based speed control policies. Evaluation of the DCB pairing with more complex tactical deconfliction tools, such as deep reinforcement learning based tactical deconfliction tool summarized in Section II [28] [29], is left for future work.

1. Ground-based Tactical Deconfliction

As showed in Algorithm 1, lines 7-10, ground-based tactical deconfliction is used for departure separation assurance. The algorithm monitors other operations at the vertiport where any given flight is scheduled to depart, and only releases it for departure if it is separated by 150m from other aircraft (arrival or departure). If the release of the flight would violate this separation requirement, the aircraft is held on the ground until the next simulation time step.

2. Airborne Tactical Deconfliction

The airborne tactical deconfliction algorithm applied is described in Algorithm 1, lines 15-27. The goal of this algorithm is for each aircraft to control its speed in such a way as to avoid LOS and therefore NMAC events with other airborne aircraft. Four separation distance thresholds are used: NMAC radius or threshold D_{nmac} ; LOS radius or threshold D_{los} ; low-separation-warning distance D_{ls} ; and high-separation distance D_{hs} , where $D_{nmac} < D_{los} < D_{ls} < D_{hs}$. When the distance of two aircraft is less than D_{nmac} or D_{los} , the speed of the following aircraft is adjusted down to the minimum cruise speed \underline{V} , and the corresponding NMAC or LOS event is recorded. If the distance is less than D_{ls} , a low-separation-warning is triggered, and the trailing aircraft reduces speed to avoid a LOS or NMAC event, up to its minimum cruise speed. Once the speed controlled aircraft detects a high-separation distance D_{hs} from the leading aircraft, it is sped up so as to reduce any airborne delays caused by the tactical deconfliction.

The airborne tactical deconfliction algorithm was run at a frequency of once every 10s. The performance of the tactical deconfliction capability would be improved by running the algorithm at a higher frequency, which we confirmed by running the algorithm at a frequency of once every second. However, because the objective of the paper is not to develop a high performing tactical deconfliction capability, but rather to test how DCB can be used to precondition traffic to support tactical deconfliction generally, the lower frequency was applied, representing a simple tactical deconfliction capability with purposely reduced performance.

C. The Demand Capacity Balancing Implementation in Simulation

A DCB algorithm is applied to strategically prevent demand from exceeding capacity at specific resources in a time window. The algorithm applies a first-requested, first-reserved allocation of demand to resources. Other more complex allocations that consider priority are beyond the scope of this paper, but are an important topic for future work. Any operations that are not allocated to resources are assumed to be delayed on departure until their entire flight no longer causes any resources to be over-capacity. We recognise that there are other approaches to resolve demand capacity imbalances strategically, such as through airborne actions such as speed control, but this is left for future work. In all cases, the only strategic action taken is to delay departure.

Demand capacity imbalances are only considered at the key constrained resources, which in this paper are defined as points in space like a crossing or merge point, as shown in baseline scenarios 1 and 2. Note that resources may also take other forms, such are areas or volumes, depending on the nature of the capacity constraint. These are not modeled in this paper. Algorithm 1 lines 7-13 describe the logic of the DCB algorithm. At each resource (crossing or merge point), the time horizon is divided into multiple time windows, each with a fixed duration S. The capacity C of the resource defines the maximum number of flights that can fly through the resource in the same time window. When the system receives new demand for the resource, it uses a mapping function $WINDOW(t + T_{est})$ to check the remaining volume of the corresponding window, where t is the current time and T_{est} is the estimated flight duration from the origin to the resource. If the demand in the window reaches the resource capacity C, the following departure will be prevented from departing until the next window that is under capacity appears.

D. Experiment Setup

The simulation setup described in Section V.A allows safety and efficiency metrics to be calculated for a given demand level and on a specific route scenario, applying tactical deconfliction and DCB. Safety and efficiency metrics can be collected and calculated applying a system capacity C and DCB window size S.

The impact of resource capacity and DCB window size on safety (using LOS and NMAC as metrics) and efficiency (using ground delay as a metric) can be explored by running multiple simulations across a range of capacity values and window sizes, at different traffic densities. These results allow the relationship between safety and efficiency to be quantified. If a specific *target level of safety* (TLS) can be identified, these results would allow the capacities and DCB window sizes to be identified that maintain safety below that TLS, and for the combination of capacity and DCB window size to be identified that minimizes delay while meeting the TLS. Selection of a TLS is up to regulators, however, and is beyond the scope of this paper. Other operational factors may also impact the window size that is most appropriate for DCB applied to UAM, but these are also beyond the scope of this paper.

Using the approach described above, safety and efficiency metrics under DCB and tactical deconfliction can be generated across a range of demand levels. The window size and capacity applied can be chosen to maximize efficiency while meeting a stated TLS or other threshold for safety.

The following section presents results applying the approach described above for each of the routing scenarios described in Section V.A.

VI. Results

In this section, results applying the DCB approach described in Section V.D are presented for the two baseline routing scenarios - merging flows in Section VI.A, and crossing flows in Section VI.B. Safety and efficiency metrics for these results are compared to those where tactical deconfliction is used without DCB, and to those where neither tactical deconfliction nor DCB is used.

Results are then presented for the simplified NYC UAM route network in Section VI.C, where the DCB capacities identified for each of the two baseline routing scenarios are applied for each of the crossing and merge points in the NYC UAM network. As in the baseline scenarios, the safety and efficiency metrics for the NYC scenario are compared to those generated by applying tactical deconfliction without DCB, and to an unmitigated baseline with neither tactical deconfliction nor DCB.

A. Experiment 1: Merging Flows

Figure 4 presents three heat maps that show average LOS duration as a percentage of total flight time for demand of 120, 60 and 30 operations per hour, from each of the two origin vertiports on route scenario 2, which simulates merging flows. For each simulation run, 10 operations were simulated from each of the origin vertiports, for a total

of 20 operations simulated per run. At each parameter setting, results were averaged across 30 simulation runs. The capacity constrained resource in this case is the merge point. Each heatmap shows results across a range of capacity values from 1 to 20 operations per DCB window, and across a range of window sizes from 50 to 400 seconds.



Fig. 4 Heat maps of LOS duration percentage on merging flows.



Fig. 5 Heat maps of NMAC duration percentage on merging flows.



Fig. 6 Heat maps of average ground delay on merging flows.

Note that a number of results show a LOS percentage of zero. This comes as a result of the statistical metrics that track safety in this work being generated using a maximum likelihood estimation approach. A zero LOS percentage

simply indicates that no LOS events were observed in the simulation, and thus the inferred safety metric tracking LOS percentage is zero. It should be expected that LOS events are rare under certain conditions, particularly under robust DCB configurations that significantly reduce risk. A more comprehensive statistical treatment of these metrics is left as future work, where upper bounds may be estimated on the safety metrics presented in this section instead of maximum likelihood estimates.

As expected, the LOS percentages decrease with decreasing demand, decreasing capacity, and increasing window size.

Figure 5 shows three heat maps demonstrating average NMAC duration as a percentage of total flight time for the same three demand values on route scenario 2, which simulates merging flows. Again, each heatmap plots results across a range of capacity values and window sizes. As expected, the NMAC percentages also decrease with decreasing demand, decreasing capacity and increasing window size. Note that the NMAC percentages are lower than the LOS percentages for the same capacities and window sizes.

Figure 6 shows the corresponding average ground delay across the demand, capacity and window sizes simulated. Average ground delay can be seen to increase with increasing demand, decreasing capacity and increasing window size.



Fig. 7 Numerical result of experiment 1: Comparison of approaches to traffic management for merging flows.

If a threshold for acceptable LOS or NMAC percentage was specified, Figures 4 and 5 would allow the set of capacities and window sizes to be identified that maintain LOS or NMAC percentage below the threshold across all simulated demand values, while Figure 6 would allow the capacity and window size in that set to be selected that minimizes delay. For example, for a maximum permitted NMAC percentage of 0.5, delay is minimized using a capacity of 3 operations per 200s DCB window, yielding an average delay of 7.9 minutes at 120 operations per hour.

Figure 7 compares safety and efficiency metrics for merging flows applying DCB to those applying tactical deconfliction without DCB, and those applying no tactical deconfliction or DCB. These results are presented across a range of demand values. The DCB results are presented for a constant DCB configuration with a capacity of 3 operations per 200 second DCB window. Tactical deconfliction is also applied in the DCB case. The results show the expected trade-off - DCB is effective at reducing LOS and NMAC percentages, but at the cost of ground delay. It is noted that LOS and NMAC percentages increase monotonically with increasing demand when no DCB or tactical deconfliction are applied, but that it stabilizes under tactical deconfliction. The tactical deconfliction algorithm applied is therefore effective at maintaining LOS and NMAC below a certain level, even at high demand. However, DCB is able to achieve much safer operations, with average NMAC percentage not exceeding the 0.5% threshold used to select the DCB capacity parameters across all demand values simulated.

B. Experiment 2: Crossing Flows

Figures 8, 9 and 10 show similar heat maps to those in Figures 4, 5 and 6, but for crossing flows. Again, for each simulation run, 10 operations were simulated from each origin vertiport, making a total of 20 operations simulated per simulation run. At each parameter setting, results were averaged across 30 simulation runs. The LOS and NMAC percentages shown are slightly lower than those for the merging flow, indicating that the capacity of the crossing point may be higher than that of a merge point. Applying the the maximum permitted NMAC percentage of 0.5 used above, and a DCB window size of 200s, to be consistent with the merge flow DCB implementation, average ground delay is



Fig. 8 Heat maps of LOS duration percentage on crossing flows.



Fig. 9 Heat maps of NMAC duration percentage on crossing flows.



Fig. 10 Heat maps of average ground delay on crossing flows.

minimized with a capacity of 7 operations per 200s DCB window, yielding an average delay of 1.4 minutes at 120 operations per hour.

In Figure 11, DCB results applying a capacity of 7 operations per 200s DCB window in the crossing flow are compared to results applying tactical deconfliction without DCB, and to results with no tactical deconfliction or DCB. Again, DCB is effective at keeping LOS and NMAC percentages approximately constant across a range of demand values. Average NMAC percentage is close to the 0.5% threshold used to select the DCB capacity parameters across all demand values simulated, but at the cost of ground delay.



Fig. 11 Numerical result of experiment 2: Comparison of approaches to traffic management for crossing flows.

C. Experiment 3: Simplified NYC UAM Network

The capacities for merging and cross flows selected in Sections VI.A and VI.B were applied to the merge and crossing points in the simulated NYC UAM network. In Figure 12 results applying DCB are compared to results applying tactical deconfliction without DCB, and to results with no tactical deconfliction or DCB. In the DCB case, a capacity of 7 operations per 200s DCB window is applied at the crossing point, and a capacity of 3 operations per 200s DCB window is applied at the crossing point, and a capacity of 3 operations per 200s DCB window is applied at the crossing point, and a capacity of 3 operations per 200s DCB window is applied at the crossing point, and a capacity of 3 operations per 200s DCB window is applied at the merge point - as identified in Sections VI.A and VI.B to maintain NMAC percentage below 0.5%. For each simulation run, 10 operations were simulated from the two origin vertiports to the West and South, while 30 operations were simulated from the vertiport to the Northeast (near LaGuardia airport). The latter number of operations was increased to ensure continued interaction between the traffic, given the shorter flight duration of traffic from the Northeast vertiport. A total of 50 operations were therefore simulated per simulation run. At each parameter setting results were averaged across 30 simulation runs, as in the previous experiments.

The NYC results in Figure 12 show similar results to those for the baseline routing scenarios, with DCB proving effective at reducing LOS and NMAC percentage, but at the cost of ground delay. At the lower demand values DCB is effective at keeping NMAC percentage close to the 0.5% threshold used to select the DCB capacity parameters, but it is exceeded at the higher demand values, where NMAC percentages are closer to 1%. These results therefore suggest that slightly lower capacities may be required to keep NMAC percentage below the 0.5% threshold, and illustrate the importance of using simulation to test across multiple scenarios.



(a) Demand VS LOS duration %

(b) Demand VS NMAC duration %

(c) Demand VS average ground delay

Fig. 12 Numerical result of experiment 3: Comparison of approaches to traffic management for the simplified NYC UAM network.

VII. Conclusion

This paper describes how simulation can be used to select DCB parameters (capacity and window size) to strategically precondition UAM operations in a way that ensures the effectiveness of tactical deconfliction systems to maintain safety at target levels. The capacities of merge and crossing points were estimated for baseline routing scenarios by simulating merging and crossing flows, respectively. The impact of DCB on those configurations was then measured by applying varying capacity values, and estimating safety and efficiency, under the application of a simple rule-based algorithm for tactical deconfliction. Additionally, we demonstrate the ability of our approach to select resource capacities that maximize efficiency while maintaining safety within a desired safety threshold by selecting capacities in baseline scenarios and applying them in complex scenarios like the NYC helicopter route network. In the two baseline scenarios and the NYC network the safety and efficiency performance of the system with DCB and tactical deconfliction, across a range of demand values. The results consistently show that while tactical deconfliction improves safety relative to no DCB or tactical deconfliction, DCB is able to maintain safety metrics at near constant levels, allowing a target level of safety to be maintained. There is, however, an efficiency cost in terms of ground delay as demand increases.

This work suggests that simulation can be effective at supporting the estimation of airspace capacity, and that DCB can be effective at maintaining safety below chosen targets levels under increasing demand. It also suggests that DCB may be an effective tool to precondition traffic for safe management by tactical systems, even when these tactical systems are relatively simple.

In this paper we have focused on scenarios in structured airspace that are deterministic in all but the generation of demand. Further research could involve testing the robustness of the DCB capacities generated by our approach by introducing additional sources of uncertainty - such as canceled and delayed flights, variable flight performance, and dynamic weather conditions. Other lines of work could involve applying the approach outlined in this paper in a setting with more complex tactical deconfliction systems, like learning-based methods. Adapting and evaluating the approach to the existing federated UTM paradigm will be another necessary extension.

The open source code for this work can be found at https://github.com/Shulu-Chen/bluesky-DCB.git.

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