# Accommodating Operational Uncertainty in Urban Air Mobility Operations with Strategic Deconfliction

Antony Evans,[1] Maxim Egorov[2] and Scot Campbell[3]
*Airbus UTM, Sunnyvale, CA, 94086, USA*

**Strategic deconfliction is a key mechanism for achieving separation between Urban Air Mobility (UAM) operations. However, operational uncertainties may degrade its effectiveness. In this paper, we quantify the effectiveness of strategic deconfliction in mitigating scheduled and unscheduled flight delays under operational uncertainty in the form of normally distributed departure and airborne errors. A range of demand levels representing early-stage UAM operations were simulated across a conceptual network of 3 vertiports in the San Francisco Bay Area. Three approaches to strategic deconfliction were simulated which varied the requirement for rescheduling into the existing schedule when an operation incurred departure or airborne error – a tight conformance requirement tied to the minimum spacing requirement; a relaxed conformance requirement comparable to that used for internal departure scheduling in Time-Based Flow Management; and no conformance requirement in which operations were never rescheduled into the existing scheduled – only replanned tactically. Results from these simulations were compared to a baseline that simulated tactical deconfliction without strategic deconfliction. Results suggest that departure and airborne delays under strategic deconfliction are highly sensitive to how much rescheduling is required into the existing schedule. Results applying strategic deconfliction with no conformance requirement, with departure and airborne error being accommodated tactically, showed significantly improved performance – even at relatively high demand and error variability. Future work should explore the safety and gaming implications of strategic deconfliction with such relaxed conformance requirements and compare its performance to using demand capacity balancing instead of strategic deconfliction.**

## I. Introduction

Forecasts indicate that there will be significant growth in the number of air vehicles operating in urban environments over the next 20 years [1,2,3]. These include Unmanned Aircraft Systems (UAS) for package delivery operations [2,3] and vertical takeoff and landing (VTOL) cargo and passenger air taxis [3]. Existing air traffic management (ATM) procedures for managing urban air traffic, which is primarily helicopters and general aviation aircraft today, are not expected to scale sufficiently to support forecast future operations, as demonstrated by human-in-the-loop simulations carried out by NASA [4]. For these reasons, new approaches to managing 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].

UTM architectures have been proposed by a number of standards bodies, regulators, and Air Navigation Service Providers (ANSP) around the world [8,9,10,11,12,13]. These are service-oriented and typically based on a federated

[1] Traffic Management Systems Architect at Airbus UTM, Senior Member, tony.evans@airbus-sv.com
[2] Research Scientist, Autonomy at Airbus UTM, maxim.egorov@airbus-sv.com
[3] System Design Lead at Airbus UTM, Senior Member, scot.campbell@airbus-sv.com

architecture in which service providers[4] make various services available to operators, including services that enable traffic management [9,10,11,12]. These services are supported by some centralized functions, e.g., to provide common information. This architecture has been refined through numerous demonstrations and trial projects [e.g., 14]. While the service-oriented architecture for UTM is widely accepted, there are differences in what functions are to be centralized, with some proposals targeting greater centralization [e.g., 12] than others [e.g., 9,10,11].

In many of the architectures described above, strategic deconfliction – resolving a predicted conflict prior to departure or well upstream of it – is proposed to support separation provision. Initial UTM demonstrations [14] have applied a first-come, first-served (FCFS) approach to strategic deconfliction, with operations needing to resolve known conflicts before departure [15]. One way to accomplish this function in a federated architecture is through a discovery service that identifies UTM service providers with which proposed operational intent may be in conflict and verifies that the UTM service provider considered the operations of other relevant service providers when planning new operational intent [16]. As UTM matures, conflict resolution may be performed through a peer-to-peer negotiation process instead of FCFS [15]. The rules governing this negotiation process are currently under development within industry standards and research groups [e.g., 17] and are still to be validated. The rules that are set to govern deconfliction are also likely to be different for strategic deconfliction, tactical (airborne) deconfliction, and detect-and-avoid systems.

Strategic deconfliction is also a key function in the FAA concept of operation for UAM [7]. However, UAM operations may experience different operational uncertainties to those of smaller UAS, and may have substantially different replanning requirements to deconflict with existing operational intent. The combination of these effects may lead to a degradation in the efficiency of strategic deconfliction for the UAM use case. Departure uncertainty particularly 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 [18], 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. 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 if operational intent is volume based [15,16,19]. Overly conservative definitions of operational intent could reduce efficiency. 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 if operations must be replanned into an already congested schedule. Furthermore, different criteria for when and how operations should be replanned may also have a significant impact on efficiency.

In this paper we attempt to quantify how strategic deconfliction can mitigate the negative consequences of operational uncertainty. Section II provides background information and describes previous relevant work. This is followed by the research objectives in Section III and our experimental approach is Section IV. Results are presented in Sections V and VI, simulating departure error and airborne error respectively. The results are followed by conclusions and recommendations for future work in Section VII.

## II. Background

In traditional ATM, separation assurance is provided by air traffic controllers. 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 because the available airspace is constrained, e.g., by convective weather, controllers may need to propagate these airborne delays upstream to ensure safe separation. Without strategic intervention, airborne holding may be required, which is undesirable both from the perspective of operating cost and because it can block off significant airspace, impacting other traffic. For this reason, when imbalances between demand and capacity are predicted, strategic traffic management initiatives 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 traffic management 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

[4] In the U.S., service providers are typically referred to as UAS Service Suppliers (USSs) for UTM and Providers of Services for UAM (PSUs) in UAM. In Europe service providers are typically referred to as U-Space Service Providers (USSPs).

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. [20]

Delays required for separation assurance can be propagated all the way back to a flight's departure airport, with the flight delayed on the ground instead of in the air. This would represent strategic deconfliction. However, in practice, this is only done when uncertainties in departure time and flight time are low. Uncertainties in the turnaround process and taxi-out contribute to departure uncertainty, while flight time uncertainties result from the relatively long flight durations of commercial aircraft and the associated challenges in predicting weather accurately along the full flight path. For these reasons, in the U.S., a form of strategic deconfliction is only applied in ATM when the remaining flight duration is relatively short and there is no convective weather on the route – meaning uncertainties are low. This is done using Time-Based Flow Management (TBFM) [20]. TBFM includes the scheduling of airborne flights at arrival meter fixes and the runway threshold, as well as the scheduling of internal departures – flights departing airports internal to the region in which TBFM is applied to airborne flights – which are given scheduled times of arrival at their destination when they are still on the ground at their origin. When uncertainties increase, e.g., due to convective weather inside the TBFM region, TBFM is typically turned off, and traffic management in the form of miles-in-trail restrictions are implemented instead.

While demand capacity balancing is specifically called out by the FAA as potentially required to support UAM operations as the number of UAM operations increases [7], it is unclear whether it is needed to accommodate operational uncertainties without excessive tactical delay, as it is in ATM. Instead, strategic deconfliction may be sufficient to pre-condition traffic so that operational uncertainties can be accommodated effectively using tactical deconfliction tools. In this paper we attempt to quantify specifically how strategic deconfliction can mitigate the negative consequences of operational uncertainty in UAM in terms of required tactical delay. A comparison between strategic deconfliction and demand capacity balancing, which is dependent on the estimated capacity of the impacted resources, is left for future work.

Scheduling and flight planning in UAM operations have been studied widely in recent years. Approaches have been proposed for terminal area scheduling that account for UAM constraints [21], and for managing dense traffic flows in unstructured airspace [22]. A vertiport scheduling algorithm has also been used to compare vertiport capacity and throughput under different vertiport configurations [23]. Ref. 19 applies approaches for strategic and tactical deconfliction to manage simulated UAM traffic and found that the trajectory predictions made pre-flight were not generally very precise due to operational uncertainties. This effect would be even greater if other uncertainties such as wind errors were simulated. One conclusion of the work was that the uncertainties associated with operational data provided prior to departure should impact the operational intent definitions – particularly the size of operational intent volumes used, if operational intent in UAM is volume based.

Ref. 18 estimates capacity and throughput for a given set of parameters that represent an operational UAM ecosystem. Using a macroscopic scenario simulator, the authors estimate the impact of the underlying infrastructure and traffic management system on throughput. Stochastic demand profiles were modeled along with uncertainties in key variables such as vehicle turn-around time at vertiports, allowing ground and airborne delays to be estimated. Disturbances such as weather and aircraft system failures were not considered. A FCFS approach to demand dispatching, landing and take-off sequencing – based on a required separation requirement – was assumed. This work does not, however, compare alternative approaches to managing that uncertainty while ensuring deconfliction. The work in the present paper seeks to extend the work of Ref. 18 in these areas.

## III. Objectives

The objectives of this paper are as follows:

1) Quantify the impact of departure and airborne uncertainty on unscheduled UAM flight delays – on the ground and in the air – across a simplified network of vertiports, at early-stage UAM demand levels.
2) Given departure and airborne errors, quantify the impact of different approaches to rescheduling strategically deconflicted operations into the existing schedule on unscheduled UAM flight delays.
3) Provide recommendations for the use of strategic deconfliction to manage operational uncertainty in UAM.
4) Provide guidance on the level of departure and airborne uncertainty that can be accommodated by strategic deconfliction in UAM at early-stage demand levels.

## IV. Approach

A macroscopic simulation was used to estimate scheduled departure delays and unscheduled departure and airborne delays for randomly generated point-to-point UAM operations across a conceptual network in the San

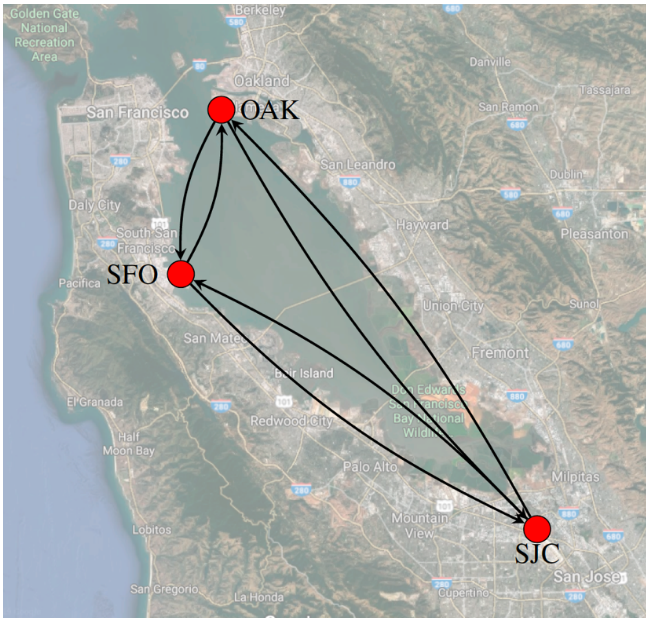


**Figure 1. Notional air taxi network of 3 vertiports in the San Francisco Bay area**

Francisco Bay Area, with vertiports located near the three major airports in the area (SFO, SJC and OAK[5]) (Figure 1). Errors in operation departure time and flight time were simulated to model operational uncertainties. Simulated delays were compared across operational uncertainties of varying magnitude and different traffic demand levels.

The impact of strategic deconfliction on these delays was quantified by comparing a baseline case with no strategic deconfliction and three different approaches to strategic deconfliction which vary the requirements for rescheduling into the existing schedule when operations fall out of conformance with their operational intent. The baseline case simulated was as follows:

1) *No strategic deconfliction*: Tactical deconfliction was applied to ensure spacing at the origin and destination, respectively, when the operations were ready for departure/arrival. No strategic traffic management was used to pre-condition the flow. This approach is comparable to nominal operations in traditional aviation when no strategic traffic management initiative is in place.

Strategic deconfliction was simulated at both the origin and destination, incurring strategic delay, with tactical replanning to ensure spacing at the origin and destination. The three alternate approaches simulated for rescheduling were as follows:

2) *Tight conformance requirement*: Operations were tactically rescheduled into the existing (strategic) schedule when departure or airborne errors were greater than half the spacing requirement. When errors were smaller, operations were still delayed to ensure spacing, but they were not rescheduled into the existing (strategic) schedule. This approach is comparable to strategic deconfliction in the ASTM draft UTM standard [16], where buffers are used to define operational intent volumes that are strategically deconflicted. Operations are rescheduled into the existing schedule when they fall out of conformance with their volumetric intent. The time buffers associated with the volumetric intent are intended to maintain separation given expected total system error. The minimum time buffer is half the spacing requirement. Larger buffers must be used when total system error increases, but this reduces efficiency because of the need to strategically deconflict the larger buffers. Increasing required spacing to accommodate expected errors – comparable to increasing time buffers in UTM volumetric intent definitions – was not explored in this paper, and is left for future research.

3) *Relaxed conformance requirement*: Operations were tactically rescheduled into the existing (strategic) schedule when departure or airborne errors were greater than specified conformance bounds. These bounds are not connected to spacing requirements. When errors were smaller than the conformance bounds, operations were still delayed to ensure spacing, but they were not rescheduled into the existing (strategic) schedule. This approach is comparable to the approach used in TBFM scheduling. Airborne operations were not rescheduled, regardless of error, which is also generally consistent with TBFM airborne metering.

4) *No conformance requirement*: No operations were rescheduled into the existing (strategic) schedule. Operations were, however, still delayed to ensure spacing on departure and arrival. This approach is equivalent to the baseline (1 above), but with strategic deconfliction to precondition the traffic so that less tactical delay is required.

Simulation assumptions and parameters are summarized in Table 1 below.

[5] San Francisco International Airport (SFO), Norman Y. Mineta San Jose International Airport (SJC), and Oakland International Airport (OAK).

**Table 1. Summary of simulation assumptions and parameters**

| Feature | Assumption |
|---|---|
| **Infrastructure** | |
| Number of Vertiports | 3 |
| Distance between Vertiports | [21.3, 48.0, 63.3] km |
| Vertiport type | Point source / sink (no surface operations or turnaround simulated) |
| Vertiport usage across operators/PSUs | Shared |
| Corridors intersection | None |
| Physical vertiport infrastructure capacity | Not modeled |
| Vertiport operations | Dependent arrivals and departures |
| Maximum number of simultaneous movements per vertiport | 1 |
| **Demand** | |
| Distribution over vertiports | Uniform |
| Distribution over time | Poisson distributed, with constant average demand across the network of [50, 60, 70, 80, 90] operations per hour |
| Simulation duration | 16 hours |
| **Operations** | |
| Vehicle cruise speed | 60 $ms^{-1}$ (117 kts), identical across operations |
| Vehicle cruise altitude | 500 m (1,640 ft) |
| Nominal (unimpeded) flight time | [6.1, 13.5, 18.5] minutes |
| Departure error | Normally distributed with mean of 0 minutes and standard deviation of [0, 1, 2, 3, 4, 5] minutes |
| Flight time error | Normally distributed with mean of 0 minutes and standard deviation of [0, 0.5, 1.0, 1.5, 2.0, 2.5] minutes |
| Fleet size | Infinite (no fleet constraint modeled) |
| **Operational Intent** | |
| File ahead time | 5 minutes for all operations |
| Format | Trajectory-based |
| **Strategic deconfliction** | |
| Strategic planning | Operation scheduling into existing schedule at origin and destination |
| Spacing requirement at vertiport | 45 seconds |
| Delay allocation algorithm | First-come, first served |
| Departure schedule conformance requirement | [-22.5/+22.5, -120/+60, -∞/+∞] seconds |
| Arrival schedule conformance requirements | [-22.5/+22.5, -∞/+∞] seconds |
| **Tactical deconfliction** | |
| Tactical planning | Operation spaced relative to preceding operation at origin and destination, respectively, when ready for departure / arrival |
| Minimum spacing requirement | 45 seconds |
| Delay allocation algorithm | First-come, first served |
| **Simulation** | |
| Number of runs per scenario | 10 |

The network of vertiports simulated is shown in Figure 1, which is identical to that simulated in Ref. 18. UAM corridors were assumed to connect all vertiports, in both directions, consistent with the corridor description by the FAA [7], and were assumed to be deconflicted from each other procedurally. All operations were simulated with a nominal cruise speed of 60 $ms^{-1}$ (117 kts) and cruise altitude of 500 m (1,640 ft). To model the vehicles in the simulation, we used a point-particle dynamic model with a hybrid proportional-integral-derivative (PID) and logic control for guidance.

Because corridors were assumed to be procedurally deconflicted and aircraft cruise speed was assumed to be similar across operations, deconfliction was only modeled at the vertiports. Since early-stage UAM operations were simulated, vertiport arrivals and departures were assumed to be dependent, so departures were deconflicted not only from other departures, but also from arrivals, and *vice versa*. The triangular network structure was used to model a more realistic representation of UAM operations, with any one vertiport deconflicting operations serving two other vertiports.

Stochastic demand was modelled between the three vertiports. The demand origins and destinations were sampled from a uniform distribution across vertiports, while the demand rate was sampled from a Poisson distribution, providing time between departures. Because no clear demand profile was available for this network, the average demand rate was assumed to be constant through the day and across routes, as in one of the cases simulated in Ref. 18. We simulated demand over a period of 16 hours, representing a single full day of operations from e.g., 6am to 10pm, and present average delays across all simulated flights and the percentage of delays above specified thresholds.

Five demand levels were simulated: 50, 60, 70, 80 and 90 operations per hour across the network. Given a simulated spacing requirement of 45 seconds, the theoretical capacity of the network is 120 operations per hour.[6] 60 operations per hour therefore equates to half of the theoretical network capacity, 80 operations per hour to two-thirds of the theoretical network capacity, and 90 operations per hour to three-quarters of the theoretical network capacity. At the five simulated demand levels there is, on average, one movement at each vertiport every 60 to 108 seconds.

With an average unimpeded flight time in the simulated network of 12.7 minutes, the average number of operations at these five demand levels that would be airborne at any one time, with no delays, would be 11 to 19.[7] These values align with the NASA definition of low-density operations in initial state UAM, well below the hundreds of simultaneous operations defined for UAM Maturity Level 4 [24]. Note that these demand levels therefore represent both early-stage UAM operations, and moderate to relatively high demand for the simulated network. Given that early-stage UAM operations will likely be across a relatively small network of vertiports, with each vertiport initially designed to support a relatively small number of operations, we consider this to be a realistic representation.

Operational uncertainty was modelled in the form of departure error, affecting when the operation is ready for departure, and airborne error, affecting when the operation is ready for landing. Figure 2 shows how these errors impact scheduled ground delay and unscheduled ground and airborne delay. Based on empirical departure errors for TBFM internal departures in traditional aviation, Ref. 25 models departure error as a Gaussian distribution with mean of -0.6 minutes (i.e., early) and standard deviation of 5.7 minutes. Because TBFM internal departures represent a close analogy to strategic deconfliction applied in UAM, we modeled departure error using a similar Gaussian distribution, with mean of zero and standard deviations varied from 0 to 5 minutes in 1-minute increments. Airborne error was also modelled using a Gaussian distribution with mean of zero, but because airborne errors are expected to be less significant in UAM than departure errors, airborne error standard deviations were varied from 0 to 2.5 minutes in 30-second increments.

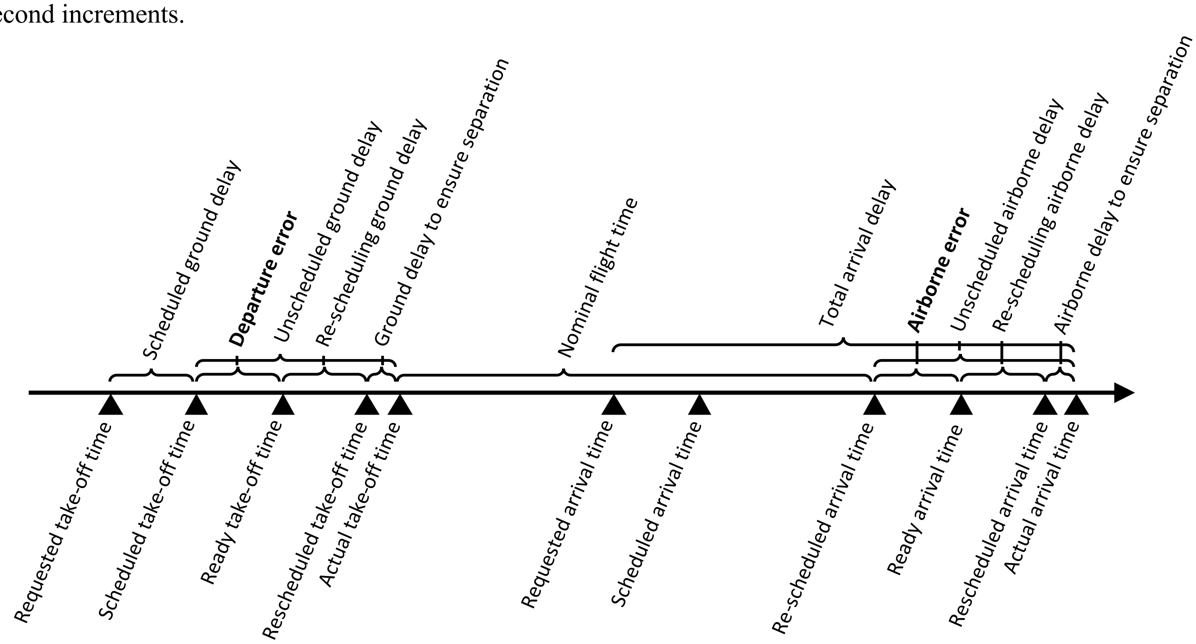


**Figure 2. Description of simulated flight delays**

Operational intent was assumed to be trajectory based, which is consistent with traditional ATM, including TBFM. However, there has not yet been consensus on whether volume-based intent, consistent with proposed UTM standards [16], or trajectory-based intent is most appropriate for UAM. The volume-based approach is a generalization of the trajectory-based approach in the special case where the volume duration (excluding buffers) approaches zero. Note

[6] A 45 second minimum spacing theoretically allows 80 movements per hour at each vertiport. With dependent arrivals and departures (2 movements per operation) at the 3 vertiports, this equates to a system capacity of 120 operations per hour.

[7] Average departure rate multiplied by average flight duration.

that when we deconflict operations in this paper, we ensure minimum spacing requirements are maintained, consistent with traditional operations carrying passengers. This means that, as shown in Figure 2, additional delay may be incurred on the ground and in the air after rescheduling to accommodate uncertainty in order to ensure minimum spacing.

Because deconfliction was only considered at vertiports, a minimum spacing requirement was only enforced at each operation's origin and destination. In this study, the minimum spacing requirement at the vertiport was set to 45 seconds, set conservatively to match the in-trail separation requirement simulated by NASA in Ref. 19. While vertiport spacing requirements for UAM remain highly uncertain, it is the resulting ratio of demand to capacity that is relevant in this study – hence the description of demand relative to the theoretical network capacity above, calculated assuming the 45 second spacing requirement. In practice, vertiport spacing requirements must be based on a safety case and may be defined by standards or regulatory bodies and the needs of operational use cases.

Strategic deconfliction incurs delay that is referred to as scheduled in that it was planned before any departure error was incurred, as shown in Figure 2. Note however that a 5-minute file-ahead time was modeled for all flights, so flights were scheduled strategically only 5 minutes before their requested departure time. The impact of file-ahead times that differ across competing operators or service providers was considered in previous work [26], which showed that file ahead time could have a significant impact on delays.

Any delay incurred in tactical deconfliction is referred to as unscheduled and was incurred after an operation had incurred delay due to departure or airborne error, as shown in Figure 2. For the approaches in which operations were rescheduled into the existing schedule when departure or airborne errors were sufficiently large (approaches 2 and 3), the criteria for rescheduling were based on departure and arrival schedule conformance limits. When applying the tight conformance requirement to rescheduling (approach 2), both departure and arrival conformance limits were set to ±22.5 seconds, which corresponds to half the spacing requirement – which is comparable to the approach to rescheduling described in the ASTM draft UTM standard [16]. When applying the relaxed conformance requirement to rescheduling (approach 3), the departure conformance limits were set to -2/+1 minute – consistent with conformance limits for departure scheduling in TBFM [27]. No arrival conformance limits were applied in this case – which is consistent with how airborne arrival metering is generally applied in TBFM. Other values for conformance limits may be appropriate for UAM, but these will be explored in future work.

Results were generated averaging across 10 runs of each scenario, with requested departure time and departure and airborne errors sampled for each flight in each simulation run.

## V. Results Simulating Departure Error

Results are presented in this section simulating departure error. In all cases, no airborne error was simulated. The sensitivity of the results to departure error variability is presented in Section V-A, and to demand in Section V-B. Results are presented for each of the approaches to deconfliction described in Section IV.

### A. Sensitivity to Departure Error Variability

For the results described in this section, departure error was sampled from a normal distribution with mean of zero and standard deviation varying from 0 to 5 minutes, while demand was sampled from a Poisson distribution with average demand fixed at 80 operations per hour across the network (equating to two-thirds of the theoretical network capacity). This rate represents relatively high demand but is not the highest rate simulated. It is intended to represent high but realistic demand for early stage UAM operations. Results are presented in Figure 3 to Figure 5. Figure 3 plots average flight delays across the range of simulated departure error variabilities for each of the deconfliction approaches described in Section IV. Figure 4 and Figure 5 plot the corresponding percentages of operations that exceed specific delay thresholds for unscheduled delay[8] and total flight delay, respectively. Figure 4 provides an indication of how many passengers would experience large, unexpected delays as a function of departure error variability and deconfliction approach. Figure 5 provides an indication of how many passengers would experience large total flight delays – including both scheduled delays that they were likely aware of when booking the flight, and unscheduled delays that were unexpected. Because passenger sensitivity to expected and unexpected delay is different, different thresholds were applied in these two figures: 5, 10 and 15 minutes for unscheduled delay in Figure 4; and 15, 30 and 45 minutes for total flight delay in Figure 5. The latter values were chosen because 15 minutes is the threshold for reporting delay by commercial airlines in the United States [28], while the former values were chosen because passenger value of time for unscheduled delay is approximately 3 times that of scheduled flight time [29].

[8] Including both unscheduled ground delay and airborne delay, although in this case airborne delays were very low because no airborne error was simulated.

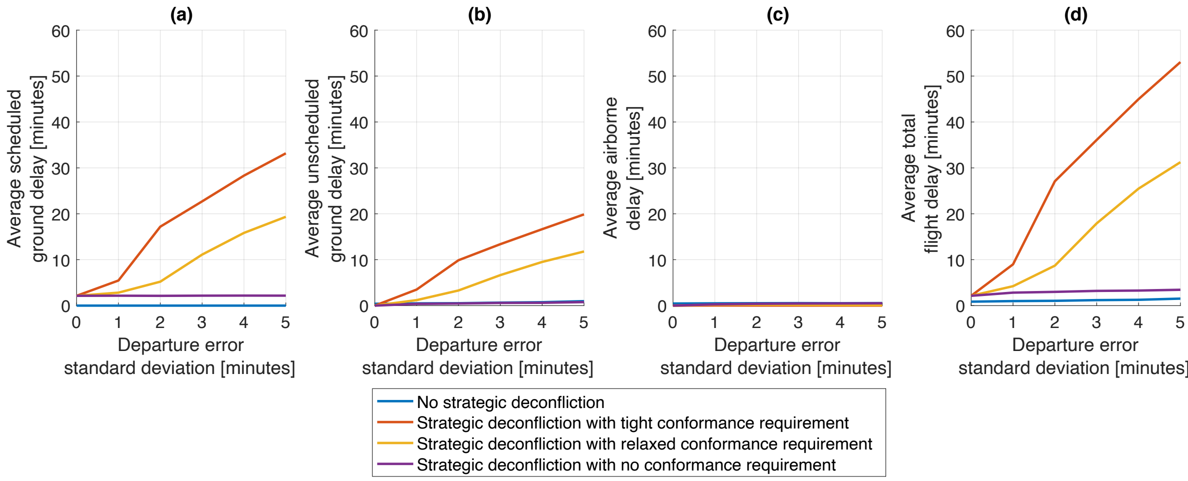


**Figure 3. Average simulated delay for demand of 80 operations per hour and departure error.**

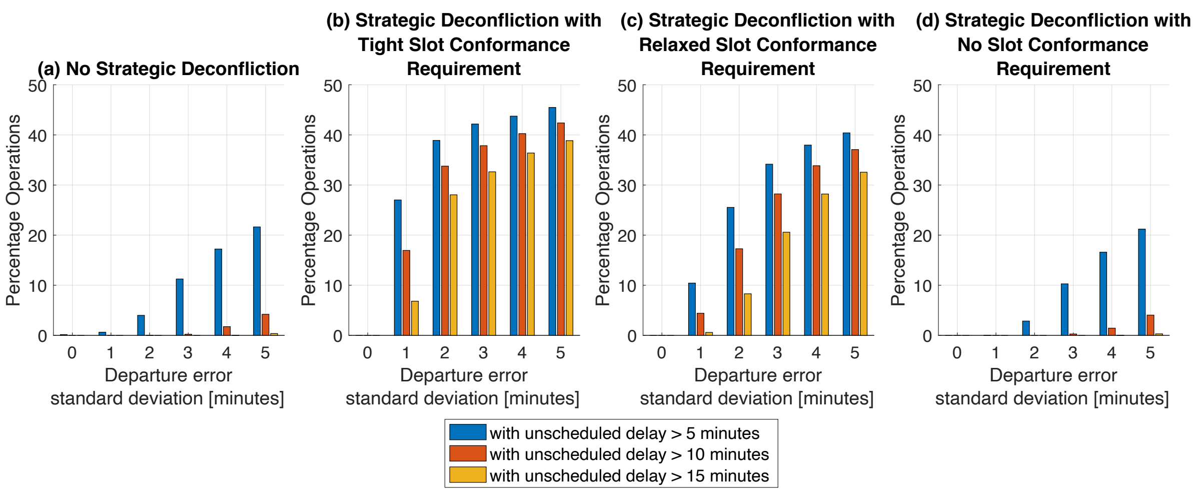


**Figure 4. Percentage of operations with unscheduled delay (ground and airborne) above thresholds, for demand of 80 operations per hour and departure error.**

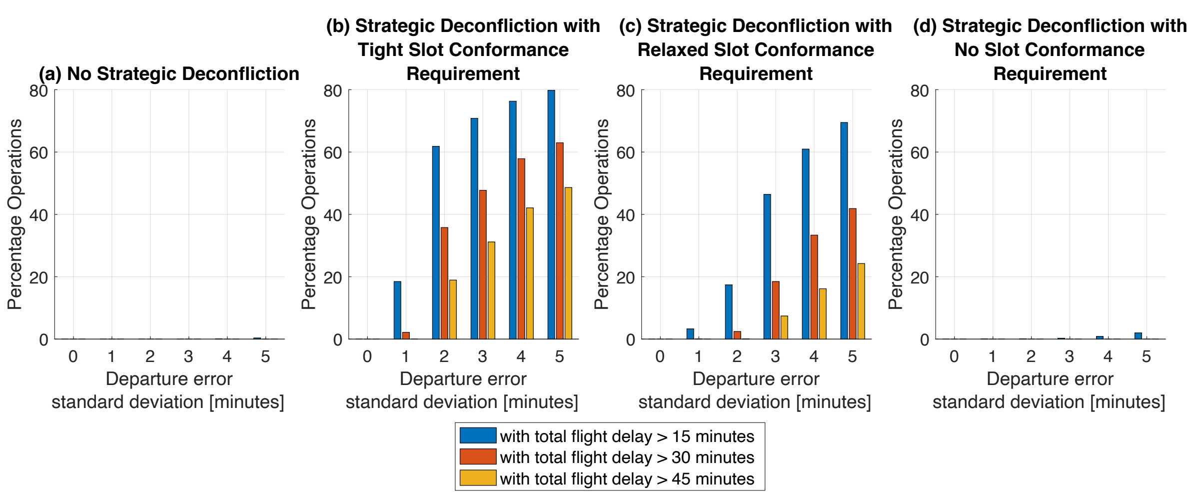


**Figure 5. Percentage of operations with total flight delay (scheduled and unscheduled) above thresholds, for demand of 80 operations per hour and departure error.**

*No Strategic Deconfliction*

In Figure 3a, the simulated approach applying tactical deconfliction only (blue lines) shows no scheduled ground delay, as expected since operations were not strategically deconflicted. Average unscheduled ground delay in Figure 3b is non-zero – because minimum spacing requirements were enforced – but increases from only 24 seconds to 60 seconds across the range of departure error variability simulated. Average airborne delay (Figure 3c) is indirectly impacted by departure error (which impacts which flights an operation must ultimately deconflict with at its destination), and is also relatively low, increasing from 28 seconds to 33 seconds across the range of departure error variabilities simulated. While airborne error was not modelled, airborne delay was still incurred under tactical deconfliction because operations were only deconflicted at their destination once airborne. Average total flight delay under tactical deconfliction (Figure 3d) accordingly varies from only 52 seconds to 91 seconds.

While average delays with no strategic deconfliction are relatively low, Figure 4a shows that a portion of operations did experience significant unscheduled delays (including unscheduled ground and airborne delay), when departure error was simulated. For a departure error standard deviation of 5 minutes, more than 20% of operations had unscheduled delay above 5 minutes, while over 4% had unscheduled delays above 10 minutes. The percentage of operations that experienced total flight delays above 15 minutes, however, is negligible, as shown in Figure 5a.

Even at relatively high demand, tactical deconfliction therefore added very little delay on average, but at higher departure error variabilities, a non-insignificant percentage of operations experienced unscheduled delays above 5 minutes. However, very few experienced total flight delays above 15 minutes. These results suggest that, under the conditions simulated in this paper, tactical deconfliction could be effective at managing departure uncertainty, even at relatively high demand. It is noted, however, that this analysis does not calculate or compare safety metrics associated with these approaches. Safety assurance requirements may make tactical deconfliction on its own unacceptable, but this is beyond the scope of the current paper.

*Strategic Deconfliction with Tight Conformance Requirement*

Results applying strategic deconfliction with tight conformance requirements (red lines in Figure 3) show average scheduled ground delays that increase from 2.1 minutes with no departure error to 33 minutes at a departure error standard deviation of 5 minutes (Figure 3a). These results show the cost of strategically deconflicting the whole trajectory (in our case at both the origin and destination vertiports) when demand is relatively high. Note that while scheduled ground delay does not explicitly account for departure error, and the same average demand was deconflicted strategically across all simulated errors, the rescheduling required because of departure error impacts the strategic scheduling of later operations. Hence the values for scheduled delay vary significantly across the different departure error variabilities simulated.

Unscheduled ground delay becomes significant when departure error variability is greater than 0. At the demand simulated in Figure 3, average unscheduled ground delay increases quickly with departure error variability, to 10 minutes at a departure error standard deviation of only 2 minutes, and reaching 20 minutes at a departure error standard deviation of 5 minutes (Figure 3b). The extent of this increase in unscheduled delay was driven to a large extent by the need to reschedule into the existing schedule at both the origin and destination whenever a departure error caused the operation to fall out of the tight conformance limits specified for this case.

Because no airborne error was simulated, average airborne delays in this case (Figure 3c) were low across all departure error variabilities – lower even than those simulated with no strategic deconfliction. Figure 3d shows that the average total flight delay applying this approach to strategic deconfliction increases from 2.1 minutes with no departure error to 53 minutes at a departure error standard deviation of 5 minutes. Even at a departure error standard deviation of 2 minutes, average total flight delay is 27 minutes. These delays are significant, and are a concern given the expected travel time sensitivities of air taxi customers. Figure 4b shows that a large percentage of operations experienced significant unscheduled delays (primarily unscheduled ground delay in this case), when departure error was simulated. For a departure error standard deviation of 5 minutes, 39% of operations had unscheduled delay above 15 minutes, while over 45% had unscheduled delays above 5 minutes. The percentage of operations with significant total flight delay is even higher – Figure 5b shows that, for a departure error standard deviation of 5 minutes, 49% of operations experienced total flight delays above 45 minutes, while 80% of operations experienced total flight delays over 15 minutes. These percentages indicate that, at relatively high demand, strategic deconfliction with tight conformance limits may not be a feasible approach to managing departure uncertainty unless expected departure errors are low.

*Strategic Deconfliction with Relaxed Conformance Requirement*

In Figure 3 we also show results applying strategic deconfliction with relaxed conformance requirements (yellow lines). As expected, the results are similar to those with tight conformance requirements, but with reduced delay values.

Average scheduled ground delays increase from 2.1 minutes with no departure error to 19 minutes at a departure error standard deviation of 5 minutes (Figure 3a) – a 42% reduction relative to the tight conformance requirement. Average unscheduled ground delay increases to 12 minutes at a departure error standard deviation of 5 minutes (Figure 3b) – a 41% reduction relative to the tight conformance requirement. This reduction in unscheduled delay was driven by the reduced need to reschedule because of the relaxed conformance requirement. Because no airborne error was simulated, average airborne delay is also low (Figure 3c), although marginally higher than for the tight conformance requirement. Average total flight delay increases from 2.1 minutes with no departure error to 31 minutes at a departure error standard deviation of 5 minutes. While this is 41% lower than for the tight conformance requirement, it still represents a significant average delay. This point is reiterated by the results presented in Figure 4c and Figure 5c. Figure 4c shows that a large percentage of operations still experienced significant unscheduled delays, when departure error was simulated. For a departure error standard deviation of 5 minutes, 32% of operations had unscheduled delay above 15 minutes, while 40% had unscheduled delays above 5 minutes. The percentage of operations with significant total flight delay is also high – Figure 5c shows that, for a departure error standard deviation of 5 minutes, 24% of operations experienced total flight delays above 45 minutes, while 69% of operations experienced total flight delays over 15 minutes. These percentages indicate that, at relatively high demand, even strategic deconfliction with relaxed conformance limits is unlikely to be a feasible approach to managing departure uncertainty unless expected departure errors are low. However, if departure error standard deviation can be maintained below, e.g., 2 minutes, the percentage of operations with unscheduled and total flight delays exceeding 15 minutes can be kept below 10% and 20%, respectively, which may be acceptable to operators.

*Strategic Deconfliction with No Conformance Requirement*

Finally, in Figure 3 we also show results applying strategic deconfliction with no conformance requirements (purple lines). In this case, the results are more comparable to those with no strategic deconfliction than to the other strategic deconfliction results just described, suggesting that it is the rescheduling of operations that is the biggest contributor to high delay. Average scheduled ground delays are non-zero – different to the no strategic deconfliction approach – but remain constant at 2.1 minutes across all departure error variabilities simulated (Figure 3a). As described above, strategic ground delay is not a direct function of departure error, since it is incurred before the error is incurred. However, with no rescheduling, departure errors have no impact on the strategic scheduling of later operations. Average unscheduled ground delay is also relatively low – increasing to only 1 minute at a departure error standard deviation of 5 minutes (Figure 3b). Average airborne delay continues to be low since no airborne error was simulated (Figure 3c), although is marginally higher than for either of the other strategic deconfliction approaches simulated. Average total flight delay increases from 2.1 minutes with no departure error to only 3.5 minutes at a departure error standard deviation of 5 minutes.

As with no strategic deconfliction, Figure 4d shows that a non-insignificant percentage of operations did experience significant unscheduled delays when departure error was simulated, although it is far less than for the other approaches to strategic deconfliction simulated. For a departure error standard deviation of 5 minutes, more than 21% of operations had unscheduled delay above 5 minutes, while 4% had unscheduled delays above 10 minutes. However, the corresponding percentage of operations that experienced total flight delays above 15 minutes is only 2%, as shown in Figure 5d.

These results suggest that strategic deconfliction with no conformance requirement may be a viable solution to managing departure uncertainty at relatively high demand. However, there may be other issues associated with strategic deconfliction with no conformance requirements, such as the risk of operators gaming the system. There may also be fairness considerations. These issues should be explored in future work.

It is noted that the results presented in this section are based on assumptions regarding key system parameters that may have specific requirements as UAM matures. This includes the default spacing requirement (45 seconds) and the file ahead time (5 minutes). The results were found to be particularly sensitive to spacing requirements, as well as parameters such as the number of vertiports in the network and the number of simultaneous arrivals and departures that can be accommodated at a vertiport. These parameters ultimately define system capacity, affecting results based on the ratio of demand to capacity. In the next section we examine the sensitivity of the results to demand.

### B. Sensitivity to Average Demand

For the results described in this section, departure error was sampled from a normal distribution with mean of zero and standard deviation fixed at 5 minutes, while demand was sampled from a Poisson distribution with average demand varying from 50 to 90 operations per hour across the network (equating to 42% to 75% of the theoretical network capacity). Results are presented in Figure 6 to Figure 8.

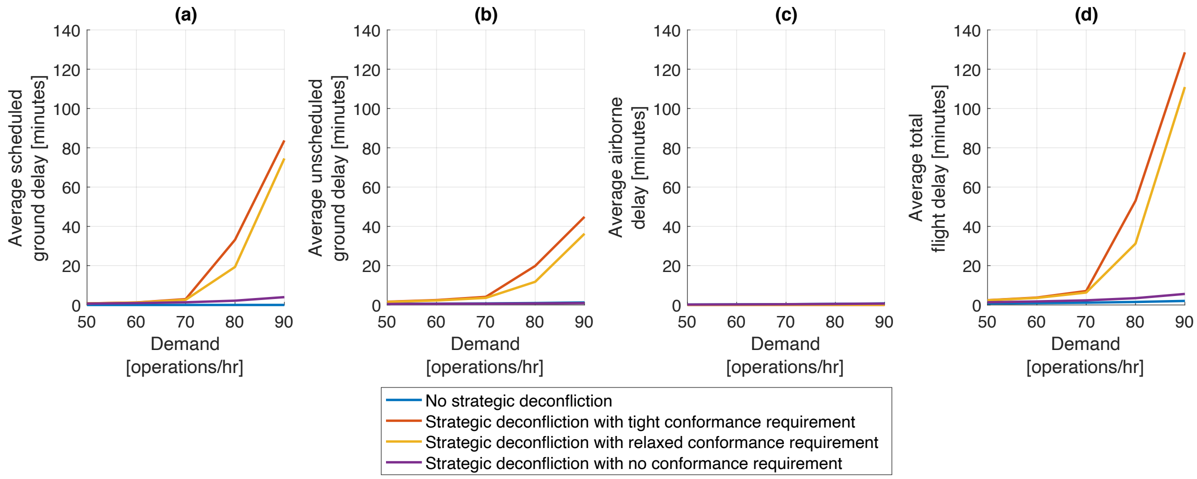


**Figure 6. Average simulated delay for departure error standard deviation of 5 minutes.**

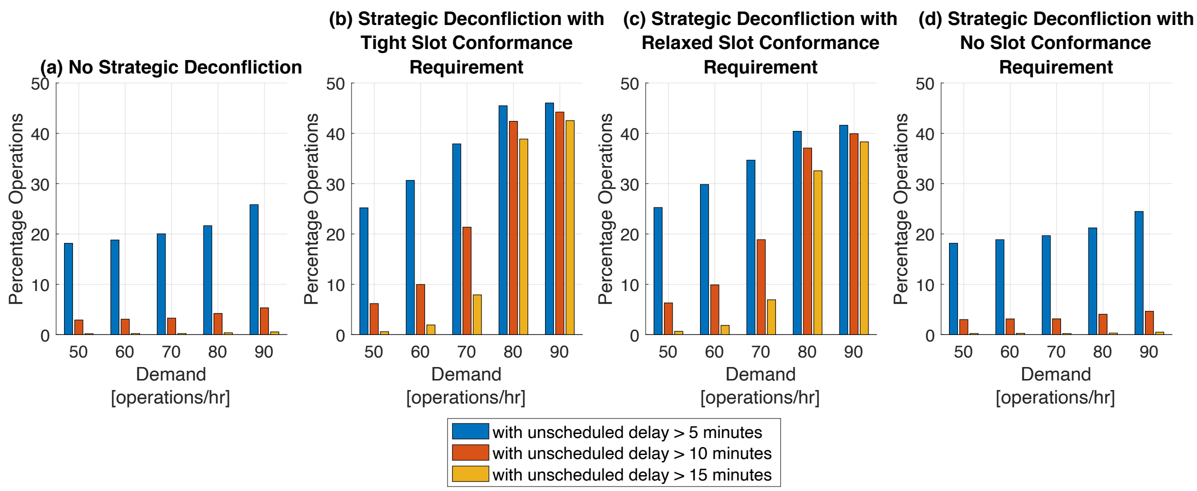


**Figure 7. Percentage of operations with unscheduled delay (ground and airborne) above thresholds, for departure error standard deviation of 5 minutes.**

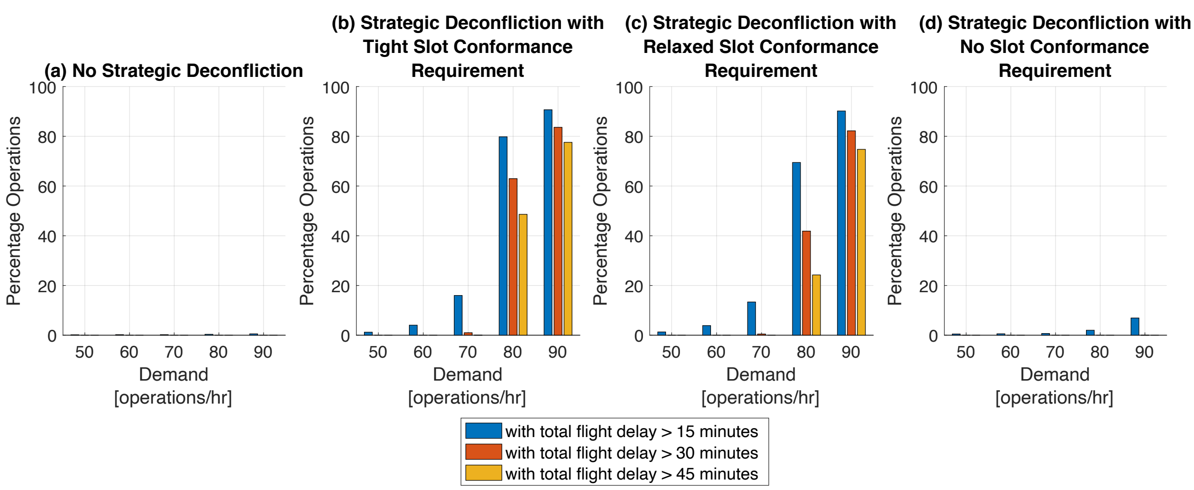


**Figure 8. Percentage of operations with total flight delay (scheduled and unscheduled) above thresholds, for departure error standard deviation of 5 minutes.**

Figure 6 plots average flight delays across the range of simulated demand for each of the deconfliction approaches described in Section IV. Figure 7 and Figure 8 plot the corresponding percentages of operations that exceed specific delay thresholds for unscheduled delay and total flight delay, respectively.

Results simulating no strategic deconfliction and strategic deconfliction with no conformance requirement for a departure error standard deviation of 5 minutes show average delays (Figure 6, blue and purple lines) and percentages of operations with delays exceeding the specified thresholds (Figure 7a and d, and Figure 8a and d) that vary relatively little with demand, increasing only slightly from 50 operations per hour across the network to 90 operations per hour across the network. The percentage of operations with unscheduled delays exceeding 5 minutes varies from just under 20% to approximately 25% for both approaches, which is not an insignificant percentage, but may be manageable for operators. Overall, these results suggest that no strategic deconfliction and strategic deconfliction with no conformance requirement may be viable solutions for managing departure uncertainty at relatively high departure error, even at relatively high demand.

The results simulating strategic deconfliction with tight and relaxed conformance requirements for a departure error standard deviation of 5 minutes, on the other hand, show average delays (Figure 6, red and yellow lines) and percentages of operations with delays exceeding the specified thresholds (Figure 7b and c, and Figure 8b and c) that vary significantly with demand. 70 operations per hour (58% of theoretical network capacity) appears to be an inflection point for the network simulated, beyond which delays applying these approaches increase significantly. The difference between the results for tight and relaxed conformance requirements is relatively small. These results suggest that these approaches may only be acceptable for managing relatively high departure uncertainty at low to moderate demand levels, unless passenger sensitivity to unscheduled delay is particularly high.

## VI. Results Simulating Airborne Error

Results are presented in this section simulating airborne error. In all cases, no departure error was simulated. The sensitivity of the results to airborne error variability is presented in Section 0-A, and to demand in Section 0-B. Results are presented for each of the approaches to deconfliction described in Section IV.

### A. Sensitivity to Airborne Error Variability

For the results described in this section, airborne error was sampled from a normal distribution with mean of zero and standard deviation varying from 0 to 2.5 minutes, while demand was sampled from a Poisson distribution with average demand fixed at a relatively high value of 80 operations per hour across the network (equating to two-thirds of the theoretical network capacity). Results are presented in Figure 9 to Figure 11. Figure 9 plots average flight delays across the range of simulated airborne error variabilities for each of the deconfliction approaches described in Section IV. Figure 10 and Figure 11 plot the corresponding percentages of operations that exceed specific delay thresholds for unscheduled delay[9] and total flight delay, respectively.

Note that the results simulating strategic deconfliction with a relaxed conformance requirement in Figure 9 (yellow lines, which are not visible), Figure 10c and Figure 11c are identical to those simulating no conformance requirement (purple lines in Figure 9, Figure 10d and Figure 11d. The reason for this is that for the relaxed conformance requirement we do not simulate a conformance requirement for arrivals – consistent with how TBFM generally manages airborne metering. For arrivals this approach is therefore identical to the approach that applies no conformance requirement. The effects of airborne error are therefore identical across the two approaches.

Simulating airborne errors, average delays applying no strategic deconfliction and strategic deconfliction with no conformance requirement (blue and purple lines in Figure 9) are almost identical to those simulating departure error (Figure 3).[10,11] The corresponding percentage of operations with unscheduled and total flight delays exceeding specific thresholds (Figure 10a and d, and Figure 11a and d), are even lower than the already low percentages simulating departure delay (Figure 4a and d, and Figure 5a and d). These results suggest that these approaches may be appropriate for managing airborne uncertainty, even at relatively high demand and high airborne error (up to 2.5 minutes standard deviation).

---

[9] Including both unscheduled ground delay and airborne delay, although in this case unscheduled ground delays were very low because no departure error was simulated.

[10] Note that the ranges of error standard deviations simulated are different, so the comparison must be made across common error standard deviations.

[11] Note also that airborne delay in Figure 9c should be compared to unscheduled ground delay in Figure 3b, since these are the delays directly affected by the airborne and departure error, respectively.

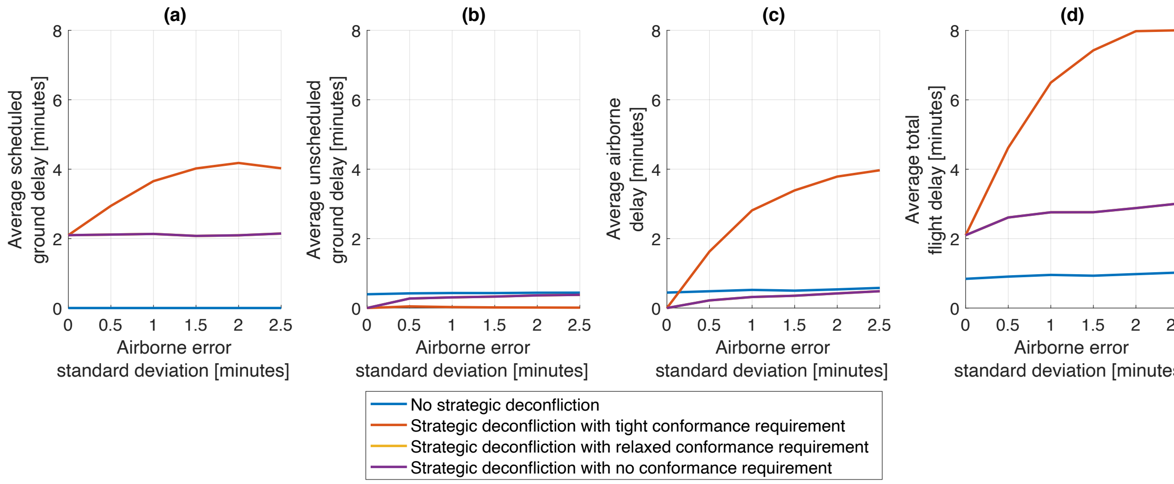


**Figure 9. Average simulated delay for demand of 80 operations per hour and airborne error.**

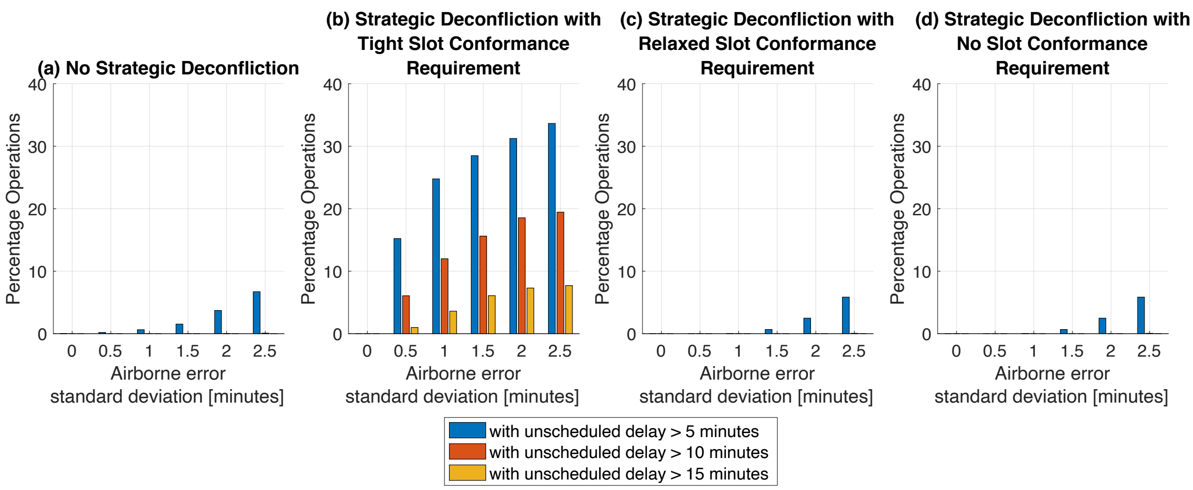


**Figure 10. Percentage of operations with unscheduled delay (ground and airborne) above thresholds, for demand of 80 operations per hour and airborne error.**

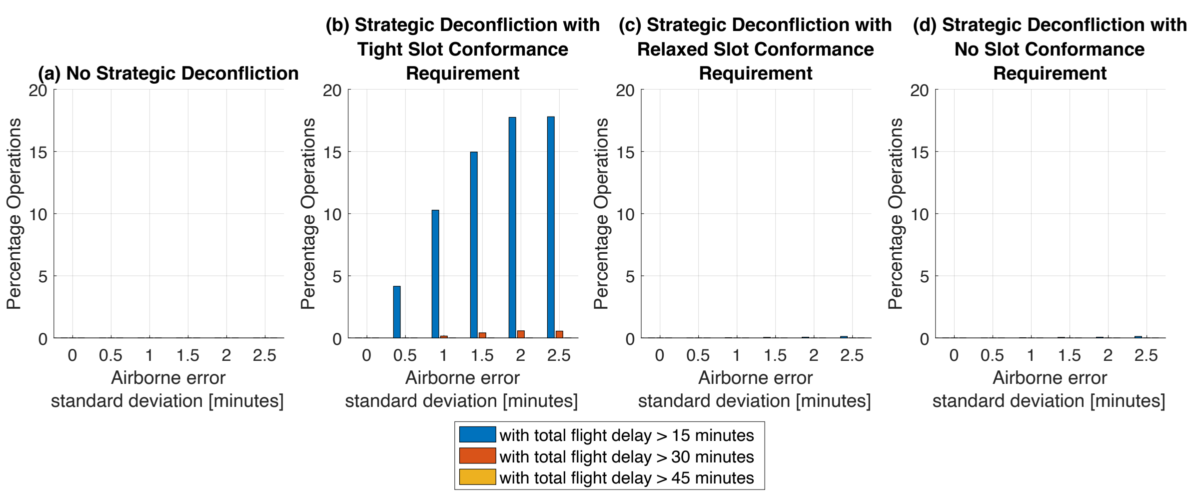


**Figure 11. Percentage of operations with total flight delay (scheduled and unscheduled) above thresholds, for demand of 80 operations per hour and airborne error.**

The average delays simulating strategic deconfliction with tight conformance requirements (red lines in Figure 9) are significantly lower than the results simulating departure error (Figure 3) – by 76% for scheduled delay, 62% for unscheduled delay, and 71% for total flight delay, all for an error standard deviation of 2 minutes. The result is average delays simulating airborne error that do not exceed 8 minutes. The corresponding percentage of operations with unscheduled and total delays exceeding specific thresholds (Figure 10b and Figure 11b) are also significantly lower than when simulating departure error (Figure 4b and Figure 5b). Part of the reason for this reduction in delay is that airborne error under this approach only requires rescheduling into the existing schedule at the destination vertiport, and not the origin, unlike departure error, which requires rescheduling into the existing schedule at both the origin and destination. In Figure 10b the percentage of operations with unscheduled delays (airborne in this case) above 15 minutes, with an airborne error standard deviation of 2.5 minutes, is still 7.7%, while the percentage above 5 minutes is 34%. The corresponding percentage of total flight delays above 15 minutes is 18% (Figure 5b). While significantly lower than the results simulating departure error, these delays are a concern given the likely energy limitations of UAM vehicles. These results indicate that strategic deconfliction with tight conformance requirements may not be feasible at relatively high demand and high airborne error.

### B. Sensitivity to Average Demand

For the results described in this section, airborne error was sampled from a normal distribution with mean of zero and standard deviation fixed at 2.5 minutes, while demand was sampled from a Poisson distribution with average demand varying from 50 to 90 operations per hour across the network (equating to 42% to 75% of the theoretical network capacity). Results are presented in Figure 12 to Figure 14. Figure 12 plots average flight delays across the range of simulated demand for each of the deconfliction approaches described in Section IV. Figure 13 and Figure 14 plot the corresponding percentages of operations that exceed specific delay thresholds for unscheduled delay and total flight delay, respectively.

Note again that the results simulating strategic deconfliction with a relaxed conformance requirement in Figure 12 (yellow lines, which are not visible), Figure 13c and Figure 14c are identical to those simulating no conformance requirement (purple lines in Figure 12, Figure 13d and Figure 14d).

Results simulating no strategic deconfliction and strategic deconfliction with no conformance requirement for airborne error standard deviation of 2.5 minutes show average delays (Figure 12, blue and purple lines) and percentages of operations with delays exceeding the specified thresholds (Figure 13a and d, and Figure 14a and d) that increase with demand, but not significantly. The percentage of operations with unscheduled delays exceeding 5 minutes remains below 10% for both approaches across all simulated demand levels. These results suggest that no strategic deconfliction and strategic deconfliction with no conformance requirement may be viable solutions for managing airborne uncertainty, even when demand and airborne error variability are relatively high.

The results simulating strategic deconfliction with tight conformance requirements for airborne error standard deviation of 2.5 minutes show average delays (Figure 12, red lines) and percentages of operations with delays exceeding the specified thresholds (Figure 13b, and Figure 14b) that vary significantly with demand. Here, 80 operations per hour (67% of the theoretical network capacity) appears to be an inflection point for the network simulated, beyond which delays increased significantly, although even at 80 operations per hour, the percentage of operations with unscheduled delays exceeding 10 minutes is nearly 20% – significant given potential energy limitations of UAM vehicles. These results suggest that strategic deconfliction with tight conformance requirements may be acceptable for managing high airborne uncertainty at low to moderate demand levels, but may not be appropriate when vehicles are highly energy constrained.

## VII. Conclusions

In this paper we quantify the effectiveness of strategic deconfliction in mitigating the impact of operational uncertainty, in the form departure and airborne error, on scheduled and unscheduled flight delays for UAM operations. A range of departure and airborne errors, and demand levels representing early-stage UAM operations, were simulated across a conceptual network of 3 vertiports in the San Francisco Bay area with dependent arrivals and departures. Three different approaches to strategic deconfliction were simulated which vary the conformance requirements, impacting when operations were required to reschedule into the existing schedule. Results from these simulations are compared to a baseline that simulates tactical deconfliction without strategic deconfliction.

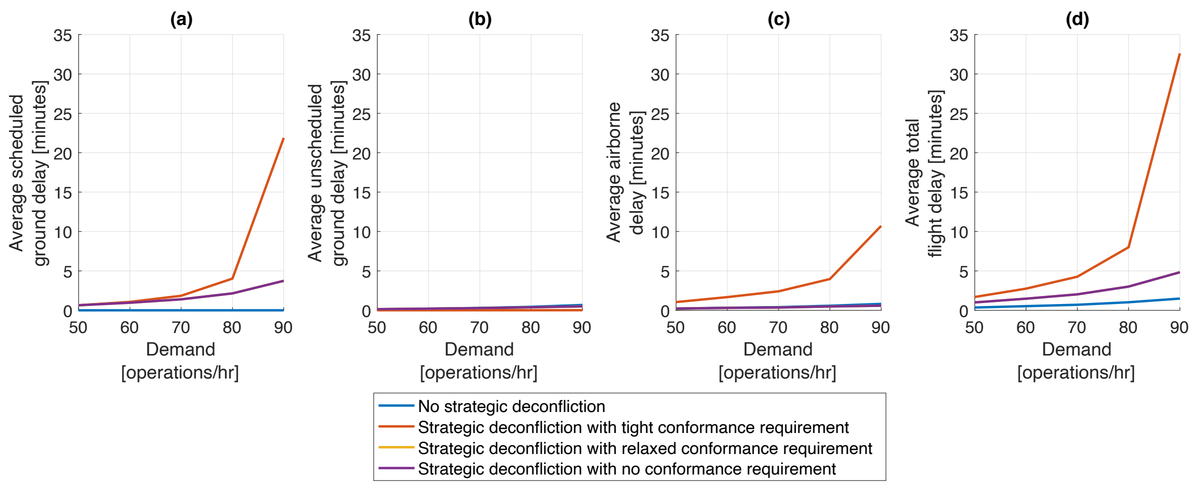


**Figure 12. Average simulated delay for airborne error standard deviation of 2.5 minutes.**

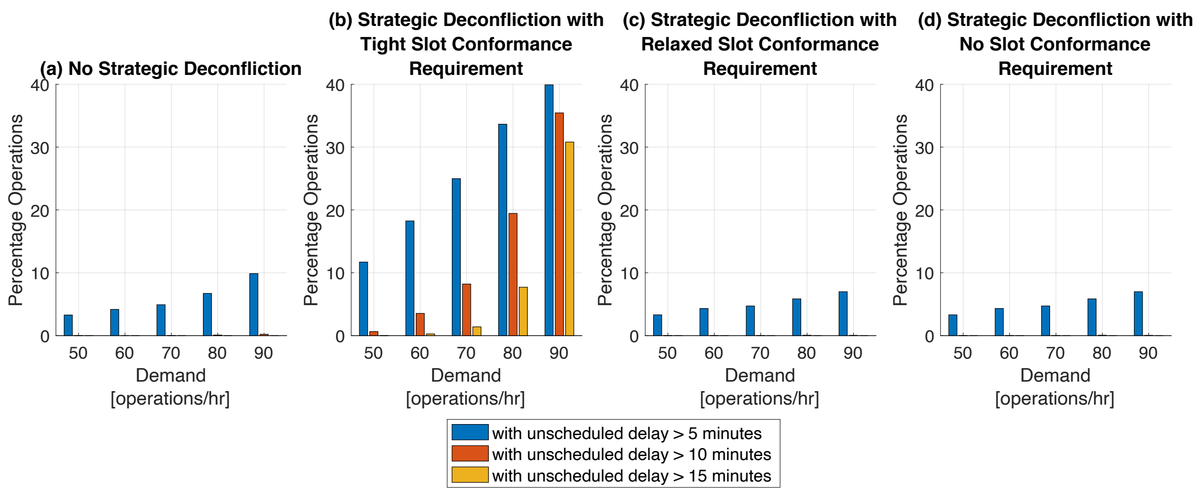


**Figure 13. Percentage of operations with unscheduled delay (ground and airborne) above thresholds, for airborne error standard deviation of 2.5 minutes.**

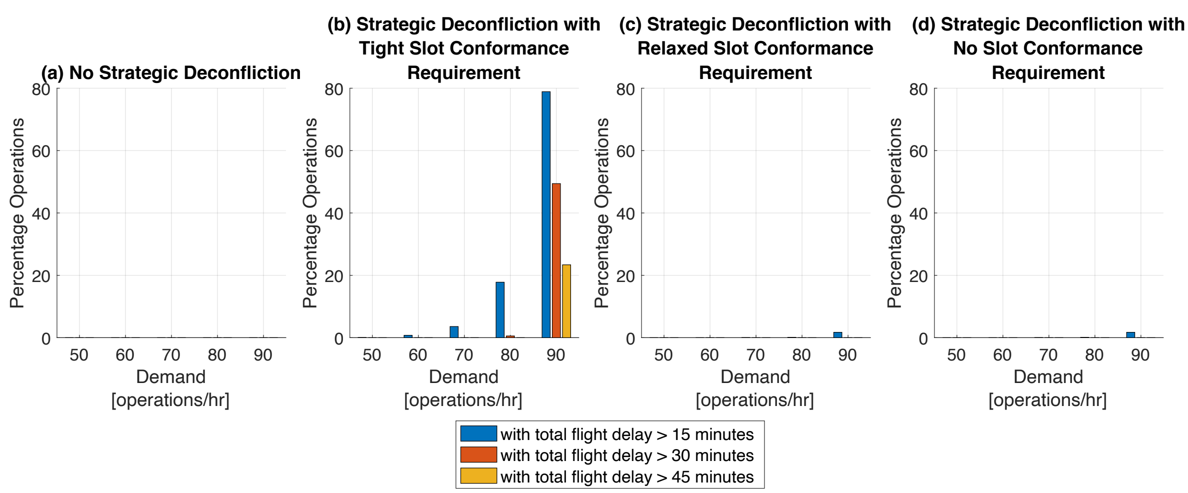


**Figure 14. Percentage of operations with total flight delay (scheduled and unscheduled) above thresholds, for airborne error standard deviation of 2.5 minutes.**

Results simulating the baseline approach show relatively low delay values, suggesting that, under the conditions simulated in this paper, tactical deconfliction could be effective at managing departure uncertainty, even at the relatively high demand and high error levels simulated. It is noted, however, that this analysis does not calculate or compare safety metrics. Safety assurance requirements may make tactical deconfliction on its own unacceptable, but this is beyond the scope of the current paper. Calculation of safety metrics is recommended for future work.

Results simulating strategic deconfliction suggest that, even at moderate demand levels and departure and airborne error variability, departure and airborne delays under strategic deconfliction are sensitive to whether rescheduling is required into the existing schedule. The simulated departure and airborne delays indicate that, because of expected UAM passenger sensitivity to travel time and expected energy limitations of future UAM vehicles, strategic deconfliction with tight conformance requirements may not be a feasible approach to managing operational uncertainty unless expected error variability or demand are low.

Results simulating strategic deconfliction with a relaxed conformance requirement show a reduction in delays relative to the tight conformance requirement, but it was not significant enough to make the approach feasible for managing departure uncertainty unless expected error variability or demand was low. However, if departure error standard deviation can be maintained below, e.g., 2 minutes, the percentage of operations with unscheduled and total flight delays exceeding 15 minutes can be kept below 10% and 20%, respectively, for demand at two-thirds of the theoretical network capacity, which may be acceptable to operators.

Results simulating no conformance requirements, with departure and airborne error being accommodated tactically, show significantly reduced delays – even at relatively high demand and error variability. These results suggest that strategic deconfliction with no conformance requirement may be a viable solution to managing departure uncertainty. However, there may be other issues associated with strategic deconfliction with no conformance requirement. Because there is no conformance requirement, there is a risk of operators gaming the system by submitting operational intent with requested departure times that are earlier than desired, in an attempt to avoid strategic delays that would result from a later (but more truthful) requested departure time. There may also be fairness considerations associated with operations that have a small departure error being delayed because of spacing requirements with earlier operations that have large departure errors. These issues should be explored in future work. One other alternative is to further relax the conformance requirements simulated with the relaxed conformance requirement. Further work is required to identify the right value for this conformance requirement, given expected error variability.

Another alternative that was not simulated in this research is the use of demand capacity balancing to strategically manage traffic, instead of using strategic deconfliction. This approach is reliant on the definition of capacity constraints for impacted resources, which should be defined in such a way as to assure the safety of tactical deconfliction. A comparison of the strategic deconfliction approaches explored in this paper with demand capacity balancing is recommended for future work.

## References


[1] Balakrishnan, K., Polastre, J., Mooberry, J., Golding, R., and Sachs, P., “Blueprint for the sky: The roadmap for the safe integration of autonomous aircraft,” *Airbus UTM*, San Francisco, CA, 2018.

[2] Jenkins, D., Vasigh, B., Oster, C., and Larsen, T., “Forecast of the Commercial UAS Package Delivery Market,” Embry-Riddle Aeronautical University, 2017.

[3] Booz Allen Hamilton, “Urban air mobility market study,” Presentation to NASA Aeronautics Research Mission Directorate, 2018, URL: https://go.nasa.gov/2MVSbth [retrieved 27 November 2019].

[4] Verma S., Keeler, J., and Edwards, T., “Exploration of Near-term Potential Routes and Procedures for Urban Air Mobility,” 19th AIAA Aviation Technology, Integration, and Operations Conference, 17th June, 2019, Dallas, Texas.

[5] Kopardekar P., Rios, J., Prevot, T., Johnson, M., Jung, J., and Robinson. J., “Unmanned aircraft system traffic management (utm) concept of operations,” AIAA Aviation Forum, 2016.

[6] Thipphavong D.P., Apaza R., Barmore B., Battiste V., Burian B., Dao Q., Feary M., Go S., Goodrich KH, Homola J, Idris HR, 2018, “Urban air mobility airspace integration concepts and considerations,” 18th AIAA Aviation Technology, Integration, and Operations Conference, 25th-29th June 2018, Atlanta, Georgia (p. 3676).

[7] FAA, “Concept of Operations v1.0 Urban Air Mobility (UAM),” U.S. Department of Transportation Federal Aviation Administration, Washington DC, 2020.

[8] Hately, A., *et al.*, “CORUS U-Space Concept of Operations,” 2016 SESAR 2020 RPAS Exploratory Research Call, EUROCONTROL, 2019.

[9] FAA, “Concept of Operations v1.0 Unmanned Aircraft System (UAS) Traffic Management (UTM),” U.S. Department of Transportation Federal Aviation Administration NextGen Office, Washington DC, 2018.
[10] FAA, “Concept of Operations v2.0 Unmanned Aircraft System (UAS) Traffic Management (UTM),” U.S. Department of Transportation Federal Aviation Administration NextGen Office, Washington DC, 2020.
[11] Swiss FOCA, “Swiss U-Space ConOps,” Swiss Federal Department of the Environment, Transport, Energy and Communications (DETEC), Federal Office of Civil Aviation (FOCA), FOCA muo / 042.2-00002/00001/00005/00021/00003, 29 March 2019.
[12] Airservices Australia, 2020. “FIMS (Prototype) System Requirements Specification,” LLAP-REQ-01, Version 0.1, 10 August 2020.
[13] EASA, “Opinion No 01/2020, High-level regulatory framework for the U-space,” European Union Aviation Safety Agency, RMT.0230, Brussels, Belgium, 2020.
[14] Rios, J., Mulfinger, D., Homola, J. and Venkatesan, P., “NASA UAS traffic management national campaign: Operations across Six UAS Test Sites.” In 2016 IEEE/AIAA 35th Digital Avionics Systems Conference (DASC), 2016, pp. 1-6.
[15] Rios, J., “Strategic Deconfliction: System Requirements”, NASA UAS Traffic Management (UTM) Project, July, 2018, URL: https://utm.arc.nasa.gov/docs/2018-UTM-Strategic-Deconfliction-Final-Report.pdf [retrieved 27 November 2019].
[16] ASTM, “*Draft* Standard Specification for Service provided under UAS Traffic Management (UTM),” ASTM WK63418, ASTM International, West Conshohocken, PA, 2020. www.astm.org.
[17] C. Chin, K. Gopalakrishnan, M. Egorov, A. Evans and H. Balakrishnan, “Efficiency and Fairness in Unmanned Air Traffic Flow Management,” in *IEEE Transactions on Intelligent Transportation Systems*, doi: 10.1109/TITS.2020.3048356.
[18] Li, S., Egorov, M., and Kochenderfer, M.J., “Analysis of Fleet Management and Infrastructure Constraints in On-Demand Urban Air Mobility Operations,” In AIAA AVIATION 2020 FORUM, 2020 (p. 2907).
[19] Verma, S.A., Monheim, S.C., Moolchandani, K.A., Pradeep, P., Cheng, A.W., Thipphavong, D.P., Dulchinos, V.L., Arneson, H., Lauderdale, T.A., Bosson, C.S. and Mueller, E.R., “Lessons learned: using UTM paradigm for urban air mobility operations,” In 2020 AIAA/IEEE 39th Digital Avionics Systems Conference (DASC), 2020 (pp. 1-10).
[20] FAA, “FAA Order JO 7210.3BB - Facility Operation and Administration,” Part 5. Traffic Management System, Chapter 18. Traffic Management National, Center, and Terminal, Washington, DC, December 31, 2020, https://www.faa.gov/air_traffic/publications/atpubs/foa_html/chapter_18.html
[21] Kleinbekman, I. C., Mitici, M., and Wei, P., “Rolling-Horizon Electric Vertical Takeoff and Landing Arrival Scheduling for On-Demand Urban Air Mobility,” Journal of Aerospace Information Systems, Vol. 17, No. 3, 2020, pp. 150–159.
[22] Egorov, M., Kuroda, V., and Sachs, P., “Encounter Aware Flight Planning in the Unmanned Airspace,” Integrated Communications, Navigation and Surveillance Conference (ICNS), IEEE, 2019, pp. 1–15.
[23] Guerreiro, N.M., G.E. Hagen, J.M. Maddalon, and R.W. Butler, “Capacity and Throughput of Urban Air Mobility Vertiports with a First-Come, First-Served Vertiport Scheduling Algorithm,” In AIAA AVIATION 2020 FORUM, 2020 (p. 2903).
[24] Price, G., Helton, D., Jenkins, K., Kvicala, M., Parker, S., Wolfe, R., “Urban Air Mobility Operational Concept (OpsCon) Passenger-Carrying Operations,” NASA/CR-2020-5001587, May 2020.
[25] Arneson, H., Evans, A.D., Kulkarni, D., Lee, P.U., Li, J. and Wei, M.Y., “Using an Automated Air Traffic Simulation Capability for a Parametric Study in Traffic Flow Management,” In 2018 Aviation Technology, Integration, and Operations Conference, 2018 (p. 3665).
[26] Evans, A., M. Egorov, S. Munn, 2020, “Fairness in Decentralized Strategic Deconfliction in UTM,” AIAA SciTech Forum, Orlando, FL, https://doi.org/10.2515/6.2020-2203.
[27] Callantine, T.J., Staudenmeier, R., Stevens, L., Coupe, J. and Churchill, A., 2019, “Electronic Departure Approval Requests in ATD-2 Daily Operations,” In AIAA Aviation 2019 Forum (p. 2934).
[28] U.S. Department of Transportation, 2018. “Technical Directive #14 – On-Time Reporting,” Research and Innovative Technology Administration, Bureau of Transportation Statistics, Office of Airline Information, Title 14 Code of Federal Regulations Part 234, Washington D.C.
[29] Evans, A.D., 2010. “Simulating Airline Operational Responses to Environmental Constraints,” Ph.D. Thesis dissertation, Department of Architecture, University of Cambridge, Cambridge, United Kingdom (pg. 65).