Preliminary Analysis of Separation Standards for Urban Air Mobility using Unmitigated Fast-Time Simulation

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***Abstract*—This research provides a preliminary analysis of various separation standards for Urban Air Mobility (UAM) operations. This study focuses on understanding and analyzing potential conflicts between UAM flights and conflicts between UAM and conventional aircraft. Fast-time simulations are conducted with a projected high-density of UAM traffic scenario and historical conventional non-UAM traffic flying under Instrument Flight Rules (IFR) or Visual Flight Rules (VFR) in Dallas Fort Worth (DFW) airspace. The conflicts are analyzed by examining losses of separation and near mid-air collisions of UAM flights and unmitigated risk of collision. A set of varied separation standards are used to investigate the impact of the new UAM operations on safety. The preliminary conflict analysis results will help inform separation standards development and in airspace and route design activities for future UAM operations.**

Keywords—Urban air mobility (UAM), fast-time simulation, separation standards, unmitigated collision risk, separation minima, conflict management, separation provision

I. Introduction

There is an increasing demand for integrating new vehicle types, innovative aviation technologies, and diverse operations into the National Airspace System (NAS), while also managing the continual growth in traditional airspace operations. Recently there is a significant movement to enable the large-scale use of electric Vertical Take-Off and Landing (eVTOL) aircraft for transporting people and/or cargo rapidly in an urban environment. NASA has been conducting the Air Traffic Management – eXploration (ATM-X) project to achieve the goals of equitable access to the airspace for all users, vehicles, and missions while also improving current operations [1].

An emerging concept of Urban Air Mobility (UAM) proposed in recent years describes expanding transportation networks to include short flights that rapidly transport people and goods, at low altitudes in and around growing metropolitan areas, as a practical and cost-effective mobility alternative for the general public [2]. As a part of the ATM-X project, the UAM Subproject performs research to understand how to develop a safe and efficient airspace system to integrate new UAM operations into the NAS [3]. Successful integration of UAM flights into the NAS is predicated upon maintaining or exceeding the level of safety and performance achieved by current operations.

Ensuring UAM vehicles maintain safe separation to avoid collisions from other vehicles is a major component of enabling safe integration and operation of UAM flights. One of the key challenges in establishing separation standards is to understand and analyze airborne conflicts between new UAM aircraft and other conventional air traffic operating under Instrument Flight Rules (IFR) or Visual Flight Rules (VFR), that are currently managed and separated by air traffic controllers. The current operations for Air Traffic Control (ATC) require relatively large separation standards between all aircraft, especially under IFR conditions, within the controlled airspace. These required separations will be a critical barrier to enable a high volume of UAM operations in the metropolitan airspace. To accommodate increasing UAM traffic demands, it is necessary to investigate and establish new separation standards for UAM operations without sacrificing the safety of existing traffic.

This research focuses on understanding and analyzing conflicts between UAM flights and conflicts between UAM and conventional IFR and VFR aircraft at different phases of UAM flights. The conflicts are analyzed by examining losses of separation (LoS) and near mid-air collisions (NMAC) of UAM flights with a set of separation standards. The analysis will investigate the impact of the new UAM operations on safety, and seek to understand the characteristics of conflicts for establishing separation standards for UAM operations.

This study conducts fast-time simulations without any tactical maneuvering of the UAM flights for avoiding a loss of separation with other aircraft. The data gathered will describe LoS rate and NMAC rate per UAM flight hour, and the unmitigated conditional risk of collision. The unmitigated conditional collision risk is defined as the conditional probability of NMACs given a loss of separation standard, without any maneuvering of UAM aircraft to avoid a loss of separation. To understand the characteristics of conflicts between UAM flights, the encounter geometries between UAM flights at various times prior to LoS are also analyzed.

The structure of this paper is organized as follows: Section II reviews the conflict management definitions, separation standards, and collision risks. The traffic scenarios developed for this work are described in Section III and the approach of this study is described in Section IV. Section IV provides a description of simulation platform and safety metrics used in this study. The results from unmitigated fast-time simulations are presented in Section V. Section VI includes a summary and future research directions.

II. Background

Conflict management is one of the key operational components of the Air Traffic Management (ATM) system that ensures safe separation of aircraft from other traffic and hazards, such as terrain, severe weather, and restricted airspace [4]. ICAO [4] states the function of conflict management will limit, to an acceptable level, the risk of collision between aircraft and hazards. Conflict management is comprised of three layers: 1) strategic conflict management, 2) separation provision, and 3) collision avoidance.

The second layer of conflict management, separation provision, is defined as "the tactical process of keeping aircraft away from hazards by at least the appropriate separation minima [4]." Thus, separation standards (minima) should be established for the second tactical layer, Separation Provision, for UAM conflict management. Separation standards can be defined as "the minimum displacements between an aircraft and a hazard that maintain the risk of collision at an acceptable level of safety [4]." The term "conflict" is defined as any point in time in which the predicted separation of two or more aircraft is strictly less than the defined separation minima [2], which is referred to as a LoS in this study.

While traditional separation standards for IFR and VFR aircraft were developed empirically based on experience and judgement of subject matter experts, recently analytical approaches have been applied to establish well clear definitions for a Detect and Avoid (DAA) system as a separation standard for integrating unmanned aircraft system (UAS) into the NAS [5, 6, 7, 8]. Two approaches are recognized in current ICAO guidance in establishing airborne separation standards: a performance-based approach and a risk-based approach [5]. The first approach is by comparison to a reference system, in which a new separation method is designed to meet the performance of an existing, accepted system, such as ADS-B separation. The second is risk-based approach to compare assessed risk against a threshold such as a target level of safety (TLS). As a minimum requirement, UAM operations should meet an appropriate level of safety consistent with the public's expectation of commercial transportation safety. The safety threshold should be determined using a risk-based approach that considers the operational area and use case, including proximate air traffic [9]. In this approach, a separation standard is typically proposed and evaluated to determine the level of risk associated with the separation standard.

For a risk-based approach, unmitigated collision risk has been initially used as a common safety metric to define and evaluate candidate definitions of "well clear" for a DAA system for safe UAS operations in the NAS [10]. The unmitigated collision risk can be measured as the conditional probability of a near mid-air collision given a separation standard volume has been penetrated. An earlier study recommended an unmitigated collision risk value of 5% for consideration of a DAA well clear (DWC) [5]. The target value of unmitigated collision risk was set to 1.5% initially so as to expand the DWC volume to enclose most of the Traffic Alert and Collision Avoidance System (TCAS) II resolution advisory alerting volume [6]. The selected DWC, however, had an undesirable vertical separation threshold of 700 ft, which is above the vertical separation of 500 ft required by VFR. Therefore, the vertical separation threshold was changed to 450 ft and the resulting desirable unmitigated collision risk for UAS operations was estimated to be 2.2% [11].

A qualitative definition of separation standard for UAM operations can be a spatial and/or temporal boundary around the aircraft to achieve an acceptable level of safety. At a minimum, a separation standard to be selected for further analyses should provide enough separation: 1) to avoid collisions or near mid-air collisions, which means it provides an acceptable probability of collision risk, and 2) to avoid excessive incursions of conflicts during the flight, which may increase the workload of ATC and/or UAM pilots to maintain the given minimum separation. If UAM aircraft encounters other aircraft equipped with TCAS II-like systems, such as DAA systems or new airborne collision avoidance system (ACAS) X systems, the interoperability issue with those systems should also be taken into account in defining the separation standards for UAM operations.

As a risk-based approach, this study conducts fast-time simulations without maneuvering any aircraft to avoid predicted conflicts, and evaluates the unmitigated collision risk of proposed DFW UAM operations with a set of separation standards. The next section describes the characteristics of DFW airspace, proposed UAM traffic, and conventional non-UAM IFR and VFR traffic used in the fast-time simulations for this study.

III. Traffic Scenarios

This study used a proposed UAM traffic scenario and historical IFR and VFR traffic in the Dallas - Fort Worth metropolitan area as a basis for the fast-time simulations.

A. DFW TRACON Airspace

The Dallas-Fort Worth area was selected for this analysis because of early interest from industry, good weather conditions, flat terrain, significant ground congestion, and the potential economic demand for quicker transportation systems. Dallas-Fort Worth TRACON (D10) is an approach control responsible for the airspace surrounding the Dallas-Fort Worth International Airport (DFW). This airspace extends 60 miles in all directions and up to 17,000 feet. The DFW TRACON is responsible not only for the primary DFW airport but also for Dallas Love Field (DAL). The D10 TRACON contains 29 airports within the DFW metroplex. The airspace above the DFW region is quite busy as multiple Class B and D airports operate in this airspace; several of the airports host many commercial and general aviation flights, creating a very unique and complex arrival and departure airspace.

In order to procedurally deconflict UAM flights from conventional IFR/VFR traffic, a set of airspace constraints and UAM route structures at DFW airspace were designed by the Airspace Procedures and Design Team from NASA's UAM Subproject, as shown in Fig. 1. The route structure for UAM operations consists of UAM Corridors, an airspace of defined dimensions in which aircraft abide by UAM specific rules, procedures, and performance requirements [2].

Fig. 1. DFW UAM restricted airspace and route network

Typically, each Corridor has two tracks, one for each direction of travel. However, some Corridors have only one bidirectional track. The UAM route structure is indicated by the light blue lines and is defined by the intersections represented as pink dots. The restricted airspace for UAM operations is shown in yellow. Vertiports are represented as green squares. The term "vertiport" is commonly used to describe the takeoff and landing locations for UAM operations and consists of one or more designated vertipads for takeoff and landing areas, and zero or more parking spaces [13].

Established UAM Corridors with tracks were procedurally separated from existing IFR/VFR routes. Lateral separation between tracks was designed as 1,500 ft based on the required navigation performance (RNP) 0.1 (600 ft plus 150 ft buffer for each side from the centerline of the route). The wake turbulence advisory requirements of 2,500 ft lateral and 1,000 ft below were used to define the UAM Corridors so that ATC can avoid giving wake advisories to both UAM flights and conventional IFR/VFR traffic in the vicinity of an airport. UAM flights should fly along the established tracks within UAM Corridors between vertiports. Outside of the dense central area, the route structure is not required, and flights can fly direct paths between their departure and arrival vertiports.

B. UAM Traffic Scenario

The UAM traffic scenarios were generated based on the airspace route structure and traffic demand developed by Virginia Tech Air Transportation Systems Laboratory using a mode-choice model for commuter trips, given a set of socio-economic factors and historical commuting patterns [12].

This traffic scenario was developed for a UAM Maturity Level (UML) 4 traffic, which is defined by NASA as approximately more than a hundred simultaneous UAM operations in a single urban area [3]. Suitable vertiport locations were also selected through an iterative, demand-driven approach for the DFW area to determine the number of likely UAM trips under a set of cost, time, and other assumptions. The input traffic scenario included a set of forecasted trips between origin and destination vertiports and a set of flight plans that are defined by a sequence of waypoints (latitude, longitude, and altitude). Each trip includes an origin, a destination, the number of passengers, trip type, planned departure time, and planned cruise altitude. The trip type defines whether the trip is mainly for passenger-carrying, for repositioning, or for clearing (described below).

The passenger-carrying UAM vehicles would conduct frequent and short-distance flights carrying two to six passengers between fixed locations through dense urban areas (on flights of 10-70 miles) and can also provide short distance movement of goods. "Repositioning" reflects operations where UAM vehicles are moved from another facility to meet passenger/operational demand at a given vertiport. "Clearing" operations represent moving excess/unused UAM vehicles from a vertiport to make room for incoming flight(s).

The UAM flight data were generated from the Advanced Trajectory Services – Toolkit for Integrated Ground and Air Research (ATS-TIGAR) tool [13], as shown in Fig. 2. Adjustments have been made to remove, relocate, or combine vertiports located inside the UAM restricted airspace. The UAM Mission Planner algorithm was used with all constraints enabled (e.g., vertiport scheduling and fleet management) but without pre-departure conflict detection and resolution to create the traffic scenarios [13]. Only one route for each origin-destination vertiport pair was selected using a route network search algorithm for this study. A portion of the route segments can be shared with other routes.

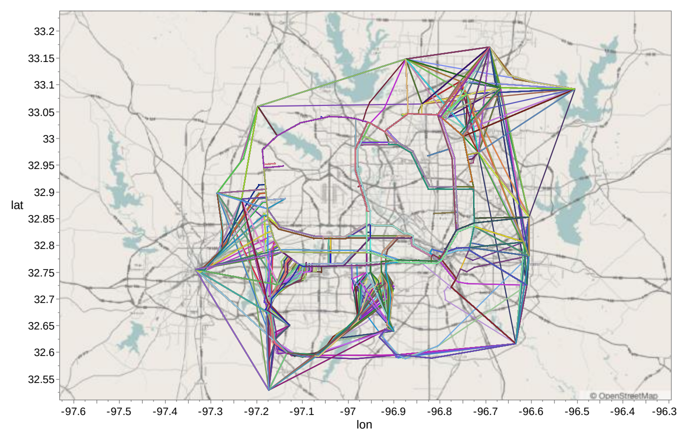

Fig. 2. All UAM flight paths generated between origin and destination vertiports at DFW airspace (with 50 vertiports)

A total of 9,986 UAM trips were generated including main passenger-carrying, repositioning, and clearing flights, with estimated simultaneous airborne flights of 225 at peak, over a 24-hour period. UAM aircraft fly on the predefined routes between origin and destination vertiports. The scenario includes the prescribed set of 46 vertiports as well as 4 storage facilities that facilitate fleet management operations in the DFW metropolitan area. For purposes of predeparture strategic conflict management, 30 seconds spacing between UAM flights at each vertiport was imposed to control the arrival and departure flow rate. The departure time of all flights was scheduled to meet the time spacing constraint at the origin and destination vertiport before taking off.

C. Conventional IFR/VFR Traffic Scenario

Conventional IFR and VFR flight paths within DFW TRACON airspace were extracted from historical ground-based radar tracks recorded on 10 non-contiguous days from June through August of 2019. The traffic scenario included real-world IFR and VFR traffic, including helicopter and unassociated (UNA) flight. UNA flights are not associated with any flight plan; their radar targets don't display a data block with flight identification and altitude information. Since UNA flights were relatively few, those flights were grouped into VFR traffic in this analysis. Most VFR aircraft fly below 2,000 ft and the average altitude of IFR aircraft was roughly 5,000 ft. The average speed of VFR traffic was around 100 knots while the average speed of IFR traffic was 220 knots. Since the proposed UAM flights operate typically below 2,000 ft, UAM aircraft may encounter slower VFR traffic more frequently than they encounter IFR aircraft.

The traffic scenarios were also composed of two runway configurations at DFW airport: five days of traffic with the South-flow configuration and five days of traffic with the North-flow configuration, as shown in Table I.

TABLE I. SELECTED TRAFFIC DATE AND RUNWAY OPERATION AT DFW

Date	Runway Operation Configuration
June 8, 2019	North Flow operation
June 10, 2019	North Flow operation
June 14, 2019	South Flow operation
June 21, 2019	South Flow operation
June 28, 2019	South Flow operation
July 7, 2019	South Flow operation
July 14, 2019	North Flow operation
August 9, 2019	South Flow operation
August 15, 2019	North Flow operation
August 28, 2019	North Flow operation

IV. Approach

Conflicts occur when the separation between two aircraft are less than the horizontal separation threshold and the vertical separation threshold; these conflicts are referred to as losses of separation (LoS) in this study. No terrain, building, or other obstructions were considered as a hazard and conflicts within a specified vertiport airspace were ignored.

A. *Encounter Set*

The proposed UAM trajectories generated based on anticipated UAM demand and route structure were superimposed on each of the 10 days of historical radar-recorded IFR and VFR traffic to generate and simulate encounters between UAM flights and encounters between UAM and non-UAM flights with realistic representative behavior of two aircraft in close proximity.

These two sets of trajectories were run through a NAS-wide, fast-time simulation tool called the Java Architecture for DAA Extensibility and Modeling (JADEM) [14] to extract encounters that feature one UAM and another UAM or conventional IFR/VFR flight that are close enough to potentially trigger a loss of separation. Each encounter has only one pair of aircraft, and thus are referred to as "pairwise encounters" for the rest of this paper. In this study, an encounter is defined as a set of UAM ownship aircraft and intruder aircraft states satisfying the following properties:

- Both UAM ownship and intruder aircraft must fly within DFW D10 TRACON airspace and below 10,000 ft MSL
- Aircraft must overlap in time
- For an encounter between UAM flights, the aircraft must be within an initial static cylinder volume with radius of 3 nmi and height of +/- 850 ft
- For an encounter between UAM and conventional non-UAM aircraft, the aircraft must be within an initial static volume with radius of 4.5 nmi and height of +/- 1,700 ft
- At least at one time step, the separation between two UAM aircraft must be less than 1.3 nmi horizontally and less than 600 ft vertically
- At least at one time step, the separation between UAM and non-UAM aircraft must be less than 2 nmi horizontally and less than 1,200 ft vertically

A typical one-day scenario used in the simulations includes a total of 9,986 UAM flights, and roughly 7,520 conventional IFR/VFR flights, on average, for a single day. A total of 79,540 unique pairwise encounters that may cause LoS were simulated to investigate the effects of candidate UAM horizontal and vertical separation standards on safety metrics in this study.

B. *Simulation Platform*

The JADEM fast-time simulation tool was extended for this study with a simple but realistic UAM vehicle model to simulate the trajectories of eVTOL UAM aircraft. JADEM was originally designed as a general-purpose simulation tool for evaluating DAA concepts and their safety characteristics for integrating unmanned aircraft into the NAS. JADEM provides a flexible and extensible software platform that includes models and algorithms for evaluating all major conflict alerting and guidance functions for UAM operations. It was built to support NAS-wide assessments and parametric trade-space studies, and also can be used for closed-loop and for human-in-the-loop simulations, as well as for flight tests that involve real aircraft.

JADEM is composed of several models as shown in Fig. 3, which include Flight Physics, surveillance Detect and Track, Alerting and Guidance, Pilot, Navigation, and Surveillance Models. The models are managed by a driver called SaaControl, which provides the required simulation functionality.

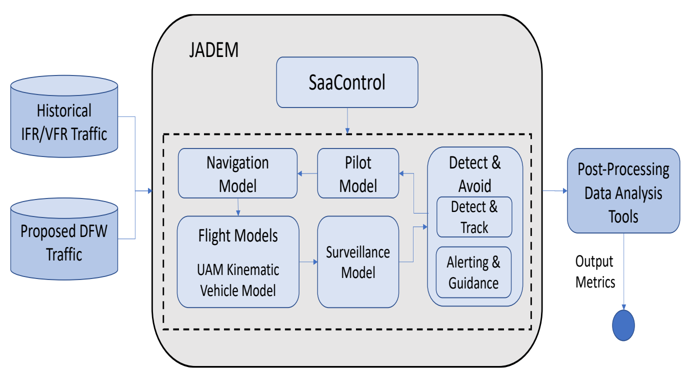

Fig. 3. Schematic of JADEM Simulation Architecture and Flow Diagram

The flight physics modeling capability is based on JADEM's Multimodal Adaptable Trajectory Generator (MATG), which relies on a Kinematic Vehicle Model, providing bank angle or turn rate, horizontal and vertical accelerations, and altitude-dependent rates of climb and descent. These parameters can be derived from real aircraft behavior inferred from track data or from Aircraft Performance Models (APM) provided by the Base of Aircraft Data (BADA). The vehicle model for UAM aircraft used in this study was a simplified version of APM (BADA-like model based on Performance Table Files) for a six passenger quadrotor eVTOL, developed by John Foster [15].

JADEM's Surveillance Model includes several simplified perfect and noisy sensor models. It supports cooperative sensor models for ADS-B, Mode-C and Mode-S, and non-cooperative onboard radar sensors. The DAA module includes the Detect & Track model, providing filters for noise reduction and source selection tracker, and Alerting & Guidance capability. JADEM was expressly designed to host different DAA algorithms. JADEM's native Generic Resolution Advisor and Conflict Evaluator (GRACE) algorithm provides alerting and "directive" guidance as the best maneuver that can be executed by a pilot or automatically by unmanned aircraft [14]. Another DAA algorithm, the Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS), can be used for "suggestive" guidance in the form of horizontal and vertical bands [10]. Therefore, it needs a DAA Pilot Model to simulate behavior of a pilot interacting with the DAA system, including delays and uncertainties inherent to human actions. Finally, JADEM provides a Navigation Model emulating some functions of a Flight Management System (FMS), Flight Director, and Mode Control Panel, such as constraint management and flight plan amendments after avoidance maneuvers.

For unmitigated simulations JADEM's Surveillance Model was configured to use the ADS-B sensors with 30 nmi range covering the entire UAM airspace for DFW. The GRACE alerting function (Generic Conflict Evaluator) was used to detect conflicts with respect to predefined separation standards, while guidance (Generic Resolution Advisor) and the pilot model were not used.

C. Safety and Operational Suitability Metrics

To better understand the potential conflicts between UAM and UAM as well as UAM and current real-world air traffic, the safety and operational suitability metrics for the conflicts were analyzed by examining the unmitigated collision risk and the rate of LoS and NMAC per UAM flight hour with a set of different separation standards.

1) Unmitigated collision risk

The unmitigated collision risk was defined as the "unmitigated" conditional probability of an NMAC after the given separation standard boundary has been penetrated, as in (1).

$$Unmitigated\ collisoin\ risk = P(NMAC/LoS) \quad (1)$$

The term "unmitigated" was used to denote that the collision risk probability did not include any maneuvering or avoidance actions on the part of either aircraft. The collision risk metric was proposed and used in defining detect and avoid (DAA) well clear (DWC) to ensure that the definitions are adequate to mitigate collision risk and to tune the parameters that define separation standards [6]. The Second Caucus of the FAA Sense and Avoid Workshop had originally suggested that an unmitigated conditional collision risk was the minimum value that could be used; lower values are typically desirable, but may result in excessively large separation boundaries. This study investigates the sensitivity of proposed separation standards on the unmitigated collision risk.

2) Rate of LoS and NMAC per UAM flight hour

As a safety and operational suitability metric, LoS rate and NMAC rate per UAM flight hours were calculated as in (2) and (3). The LoS rate represents how frequently UAM flights have LoS per hour, resulting in requiring ATC and UAM pilot to monitor and take appropriate action to avoid the predicted conflict. Higher LoS rates will increase the ATC and UAM pilot workload during the flight. The unmitigated NMAC rate, independent of separation standards, represents how frequently UAM aircraft penetrate the collision volume with other aircraft if the UAM aircraft does not maneuver, which is a critical safety metric in calculating acceptable collision risk of separation standards.

$$LoS\ Rate = \frac{Number\ of\ LoS}{Total\ duration\ of\ all\ UAM\ flight\ hours} \quad (2)$$

$$NMAC\ Rate = \frac{Number\ of\ NMAC}{Total\ duration\ of\ all\ UAM\ flight\ hours} \quad (3)$$

V. Simulation Results

The safety metrics were analyzed for the conflicts between UAM flights and the conflicts between UAM flights and non-UAM conventional IFR/VFR traffic. Table II lists ranges of separation standard parameters investigated in the safety analysis of conflicts between UAM flights.

A. Analysis of Losses of Separation and NMAC Rate

First, LoS and NMAC rate per UAM flight hours were analyzed for the conflicts between UAM aircraft as a function of separation standards by UAM flight phase. Total flight hours of all UAM flights for a day used in this study was 1830.18 hours. The LoS and NMAC rate per UAM flight hours can inform how frequently UAM need to maneuver and may require ATC intervention in controlled airspace. If the pilot is required to coordinate a resolution maneuver with ATC to resolve a predicted LoS, each conflict alert may cause a disruption to the controller's operations.

TABLE II. PARAMETER SPACE FOR SEPARATION STANDARDS FOR CONFLICT BETWEEN UAM FLIGHTS

Separation Standards	Parameter Space
Horizontal separation (ft)	750, 1000, 1250, 1500, 1800, 2200, 3000, 4000, 5000, 6500
Vertical separation (ft)	150, 300, 450

A vertiport airspace was defined as a cylindrical volume with a 2,750 ft radius and 1,100 ft height in MSL from a vertiport. LoS and NMAC were analyzed based on the flight phase of UAM: departure, arrival, and enroute. For example, If LoS or NMAC occurs when the UAM flight was within a departure vertiport airspace, it is categorized as departure phase. If UAM flight was between departure and arrival phase, then it is categorized as enroute flight phase.

As shown in Fig. 4, LoS rate per UAM flight hour was very high; ranging from 2 to 26 as separation volume increases. This means that UAM flights violated a given separation minima every 2 to 30 minutes based on the separation standard threshold settings. As horizontal and vertical separation increased, the LoS rate increased as expected. The LoS rate increased noticeably when the horizontal separation increased to 1,800 ft. There was a higher LoS rate during the enroute phase, compared to the LoS rate during departure or arrival flight phases.

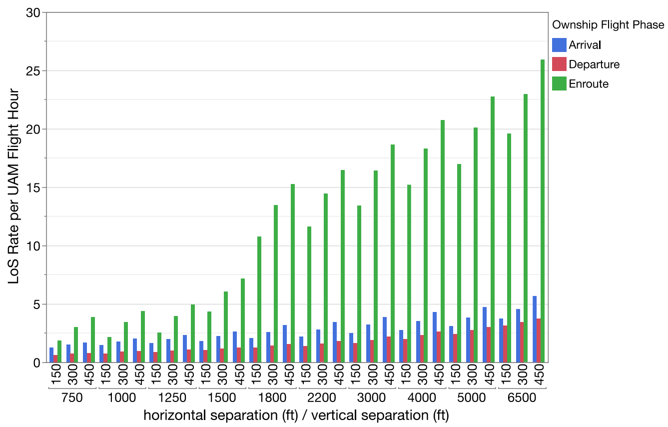

Fig. 4. Loss of separation rate with UAM aircraft per UAM flight hour

These results are due to the 1,500 ft of UAM routes separation by design. If the horizontal separation is larger than 1,800 ft, the UAM flight will have more than 10 LoS per hour even with the smallest vertical separation of 150 ft and the UAM pilot may need to maneuver very frequently to avoid conflicts with other UAM flights.

Fig. 5 shows the NMAC rate with other UAM flights per UAM flight hour by flight phase. Two different NMAC volumes were investigated. With the traditional NMAC volume with the 500 ft radius and +/- 100 ft vertical separation, UAM aircraft had an NMAC with another UAM aircraft approximately every 50 minutes during the enroute phase. The NMAC occurred once every 67 minutes, which was closed to the NMAC rate during the enroute phase. The NAMC rate during departure was less than the NMAC rate during arrival phase since the departure time of all flights was scheduled to meet the 30 seconds of time spacing between UAM flight at the vertiport. New arrival and departure procedures may be required to reduce NMAC incidents within the vertiport airspace. When the NMAC volume was reduced to 100 ft of radius and +/-20 ft of height, the NMAC rate was considerably reduced to once every 4.5 hours (about 80% decrease) during the enroute flight phase. A new quantitative definition of NMAC may be required to be appropriately tailored for operations by these smaller new airspace entrants, such as smaller UAS and UAM vehicles, and their risk analysis [16].

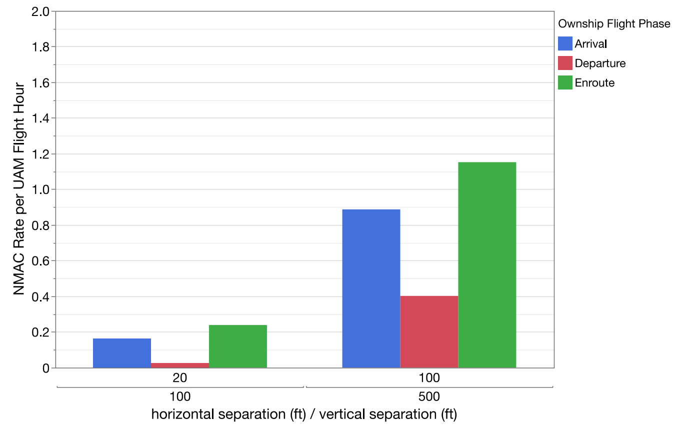

Fig. 5. NMAC rate with UAM aircraft per UAM flight hour

The separation standards investigated for the safety between UAM aircraft and conventional non-UAM aircraft were listed in Table III. For this study, the range of horizontal separation threshold varied from 2,500 ft to 1.5 nmi, which is the required legal separation of VFR aircraft from all other VFR/IFR aircraft [17].

TABLE III. PARAMETER SPACE FOR SEPARATION STANDARDS FOR CONFLICT BETWEEN UAM AND CONVENTIONAL NON-UAM FLIGHTS

Separation Standards	Parameter Space
Horizontal separation	2500 ft, 3000 ft, 4500 ft, 1.0 nmi, and 1.5 nmi
Vertical separation	500 ft

No vertical separation other than 500 ft was explored for conflicts with conventional IFR and VFR traffic, in order to retain the legal VFR traffic separation of 500 ft, and reducing the vertical separation threshold would undesirably increase the required horizontal separation threshold to meet unmitigated collision risk.

As shown in Fig. 6, there was notably lower LoS rate with conventional IFR/VFR flights, compared to the LoS rate against UAM flights. For example, when the horizontal separation of 3,000 ft was used, UAM aircraft lost the separation approximately every 2,400 minutes with conventional flights while UAM aircraft lost the separation every three minutes during the enroute flight phase. UAM aircraft flying on the proposed UAM routes rarely encountered non-UAM IFR/VFR aircraft during the flight. Even with the current legal VFR separation (1.5 miles of horizontal separation and 500 ft of vertical separation), UAM flights experienced a conflict (i.e., LoS) at every 8.6 hours during the enroute flight phase. There were relatively lower LoS rates with conventional aircraft during arrival and departure flight phases. The LoS rate was considerably reduced to one conflict at every 25 hours, a 65% decrease, when the horizontal separation reduced from 1.5 nmi to 4,500 ft.

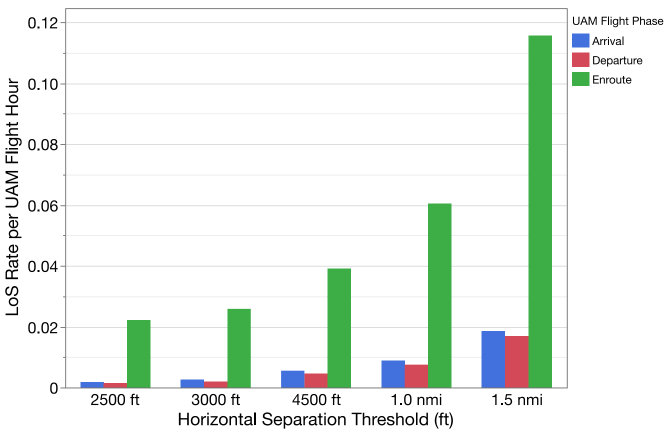

Fig. 6. LoS rate with non-UAM aircraft per UAM flight hour

To compare UAM aircraft encounters between IFR or VFR aircraft during enroute flight, the LoS rate was compared by the intruder type as shown in Fig. 7. As expected, UAM flights typically had more conflicts with VFR aircraft across all separation standards since the UAM routes were designed to be separated from the existing IFR routes.

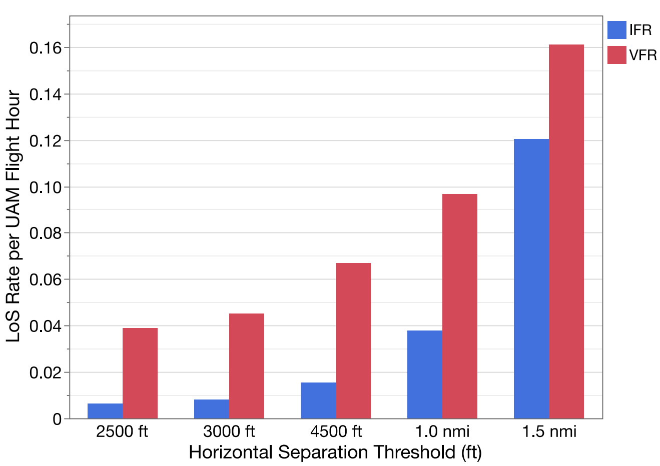

Fig. 7. LoS rate with non-UAM aircraft per UAM flight hour during en route flight phase by intruder aircraft category

Fig. 8 illustrates the average NMAC rate per UAM flight hour with conventional non-UAM aircraft, during the enroute flight phase over 10 days, by DFW airport traffic flow configuration and intruder category. UAM aircraft had more NMAC incidents with VFR aircraft than IFR aircraft in both South and North traffic flow configurations. In South flow, the NMAC rate (0.00007 per UAM flight hour) with IFR aircraft was a much lower than the NMAC rate (0.00126 per UAM flight hour) with VFR aircraft as UAM routes were designed to be separated from the existing IFR routes in the DFW South traffic flow configuration.

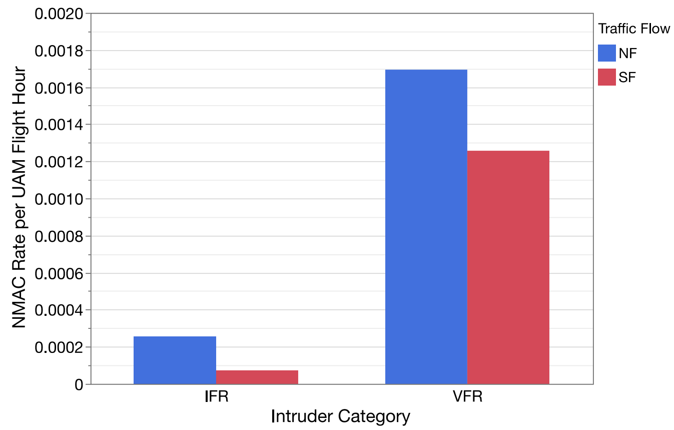

Fig. 8. NMAC rate with non-UAM aircraft per UAM flight hour during en route flight phase by intruder aircraft category and DFW traffic flow (NF: North traffic flow and SF: south traffic flow)

B. *Conditional Collision Risk Analysis*

The unmitigated conditional collision risks were computed using a post-processing data analysis tool with the JADEM simulation results. Fig. 9 shows the unmitigated collision risk for conflicts between UAM aircraft during the enroute flight phase. There was a high probability that an NMAC occurs given that the separation volume between UAM flights decreases as expected. When the horizontal separation threshold was reduced to lower than 1,500 ft and as the vertical separation decreased, the collision risk increased notably. Since the UAM routes were designed to be separated by 1,500 ft horizontally and all UAM flights were operated within that UAM airspace including the route network, there was a higher chance of an NMAC incident once the UAM flights were within this horizontal separation threshold of 1,500 ft. On the other hand, there was little benefit of reducing the conditional collision risk when the horizontal separation threshold was larger than 1,800 ft. There was also a small effect of vertical separation on the collision risk when the horizontal separation threshold was larger than 1,800 ft.

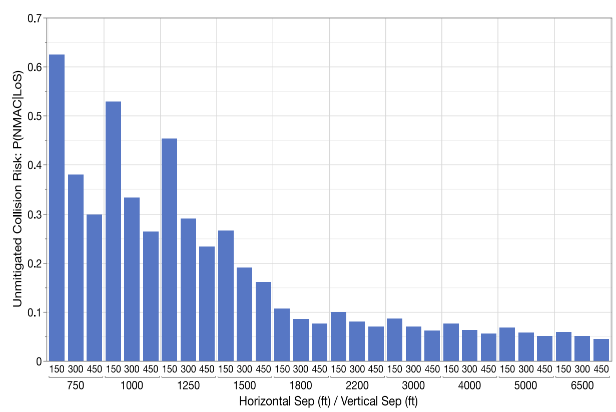

Fig. 9. Unmitigated conditional collision risk for conflicts between UAM flights during enroute flight phase

The contours for conflicts between UAM flights during enroute flight phase shown in Fig. 10 were produced by MATLAB from values of the unmitigated conditional collision risk at grid points. If the unmitigated collision risk needs to be less than 5%, the horizontal separation threshold should be more than 5,000 ft given that the vertical separation is set to 450 ft. If the vertical separation is reduced to less than 300 ft, the resulting required horizontal separation should be larger than 6,500 ft, which causes a considerably increased LoS rate, as shown in Fig. 4. If the unmitigated collision risk needs to be less than 10%, the horizontal separation should be more than 1,800 ft with a larger than 200 ft of vertical separation. To meet the estimated desirable unmitigated collision risk of 2.2% for UAS operations, the separation standards for UAM operations should be much larger than the 6,500 ft of horizontal separation and 450 ft of vertical separation, which may not be operationally practical.

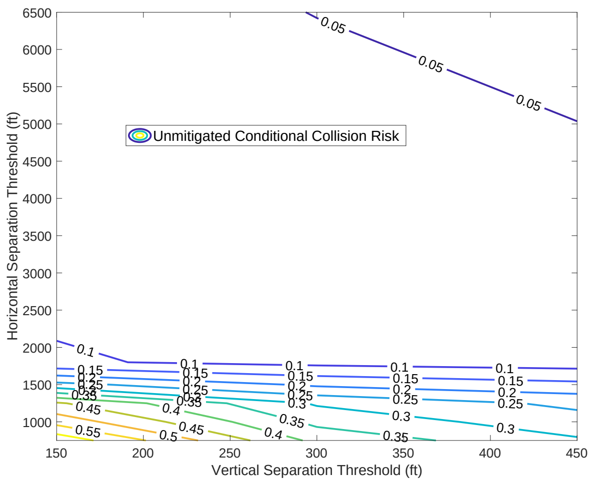

Fig. 10. Contour plot for unmitigated conditional collision risk given a loss of separation (for conflicts between UAM flights during enroute flight phase)

Aggregated unmitigated collision risk between UAM and conventional IFR and VFR traffic over 10 days was analyzed by DFW traffic flow configuration as shown in Fig. 11.

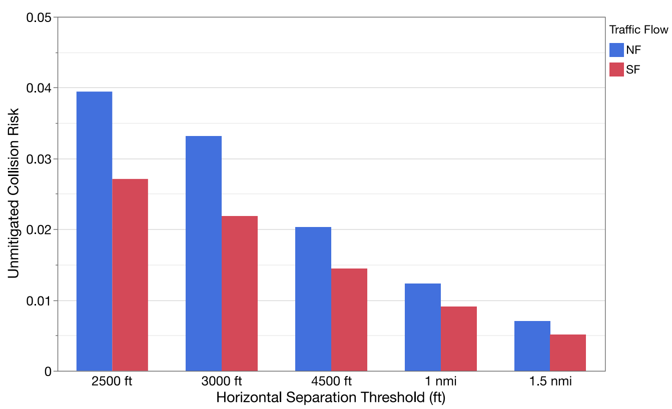

Fig. 11. Aggregated unmitigated collision risk between UAM and conventional non-UAM flights during the enroute flight phase by DFW airport traffic flow

Compared to the unmitigated collision risk between UAM flights, there was a notably lower collision risk between UAM and conventional non-UAM traffic, specifically for South traffic flow configuration since the UAM routes were designed to be separated from the existing IFR routes. The unmitigated collision risk was less than the estimated desirable unmitigated collision risk of 2.2% for both traffic flows when the horizontal separation threshold was bigger than 4,500ft with the vertical separation of 500 ft.

The aggregated unmitigated collision risk over 10 days was also grouped and analyzed by intruder aircraft category (IFR and VFR) as shown in Fig. 12. The collision risk against all conventional non-UAM aircraft (even with VFR traffic) was less than 5% even with the smallest 2,500 ft of horizontal separation regardless of the traffic flow configuration. To meet the estimated desirable unmitigated collision risk of 2.2% for UAS operations, the separation standards for IFR intruder aircraft should be larger than 3,000 ft of horizontal separation. If the horizontal separation threshold is larger than 4,500 ft, the collision risk for VFR went also down to below 2.2%.

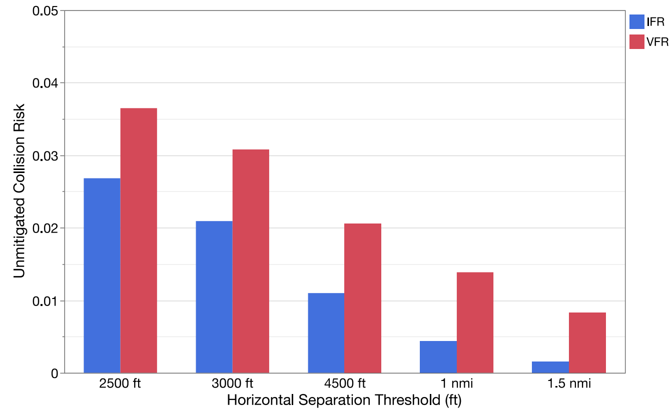

Fig. 12. Aggregated unmitigated collision risk between UAM and conventional non-UAM flights during enroute flight phase by intruder aircraft category

Since the recommended values of 5% and 2.2% for unmitigated collision risk were based on an open-loop risk recommendation, there is no guarantee that 2.2% of unmitigated collision risk is low enough to meet safety metric targets without additional safety analysis. On the other hand, the required level of safety might be achieved in a closed-loop risk analysis with a conflict alerting and guidance system with even higher values of unmitigated collision risk. Therefore, smaller separation standards with a larger unmitigated collision risk can be selected as the primary candidates for further mitigated safety analysis to evaluate the collision risk ratio for measuring how NMAC risk can be reduced effectively, if the UAM pilot executes a maneuver to mitigate the conflicts.

C. *Encounter Geometry Analysis*

This study also investigated the encounter geometries, in terms of relative horizontal angle (i.e., bearing angle) and relative horizontal range between UAM flights at some time prior to LoS, to better understand the relative state that can be assumed to no longer be acceptably safe when violated. Relative bearing refers to the horizontal angle between the ownship's heading and the location of another aircraft. Intruders can be approaching from any horizontal aspect, which means they may be converging, overtaking, overtaken, or head-on encounters per the right-of-way rules in 14 CFR 91.113. The majority of intruders was approached from the front of the ownship as shown in Fig. 13.

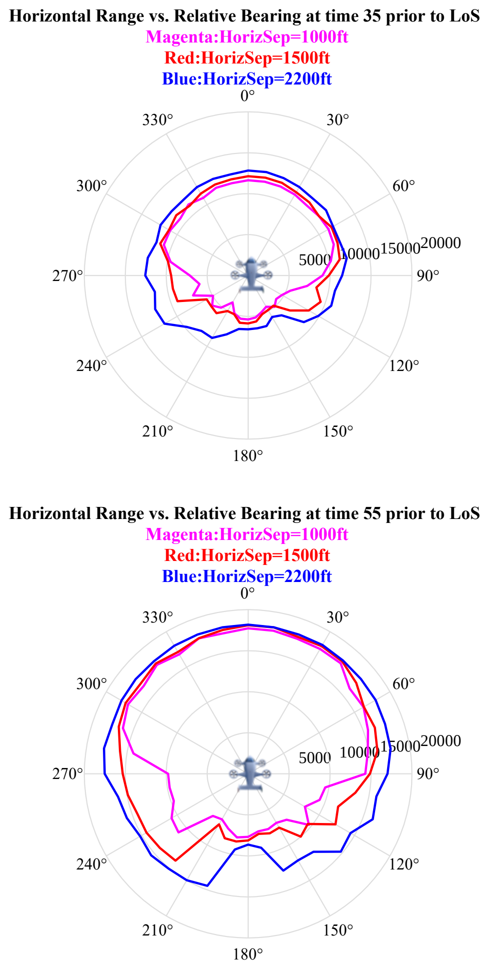

Fig. 13. Relative bearing between UAM flights at time 55 seconds and 35 seconds prior to LoS

Three horizontal separation thresholds (1000 ft, 1500 ft, and 2200 ft horizontal separations) for UAM aircraft were selected based on the unmitigated collision risk shown in Fig. 10. The vertical separation threshold was set to 450 ft since smaller separation thresholds provide larger unmitigated collision risk. The first separation standard with 2,200 ft of horizontal separation was selected since that is the noncooperative DWC definition for UAS. There was also little effect on the unmitigated collision risk with separation standards larger than 2,200 ft of horizontal separation. The second separation standard with 1,500 ft of horizontal separation was selected since most of the UAM routes were separated by 1,500 ft laterally by route design. The last separation standards with 1,000 ft of horizontal separation was selected to see the effect of the reduced horizontal separation standard even though it has 25% of unmitigated collision risk given the LoS.

The asymmetric relative state between two UAM aircraft at 35- and 55-seconds prior to LoS indicates that conflicts occur more frequently with traffic approaching head-on and crossing with a higher closure rate than traffic from behind the ownship. This is because all UAM aircraft fly at the same speed during the enroute phase, thus overtake conflicts are less likely to occur. This result suggests that those head-on and crossing intruder aircraft should be carefully taken into account in further analysis and establishment of separation standards for UAM operations. The traffic approaching from behind the ownship (e.g., traffic that are outside of +/- 120 degrees of azimuth angle of the ownship) may have a responsibility for maintaining a safe separation with the leading aircraft.

VI. Summary

This study evaluated a set of potential separation minima for the proposed UAM operations in DFW TRACON airspace using safety and operational suitability metrics such as unmitigated conditional collision risk given a LoS and the LoS and NMAC rate per UAM flight hour. The conflicts between UAM flights and conflicts between UAM and non-UAM flights were analyzed to evaluate the metrics using the proposed UAM traffic and historical conventional IFR and VFR traffic.

The results from this preliminary analysis show that given the current concept of UAM airspace design (i.e., UAM routes) and a high density of traffic scenario, there is a high unmitigated LoS rate between UAM flights if there is no conflict management; it ranges from 2 to 26 LoS per UAM flight hour as separation volume increases from 750 ft to 6,500 ft horizontally and from 150 ft to 450 ft vertically. By design of the route structure, when the horizontal separation minimum is larger than 1,500 ft, the LoS rate during the enroute flight phase considerably increases if there is no mitigated action to avoid the conflicts. Such separation standards increase the workload of UAM pilot and the need for ATC's intervention as UAM flights deviate from their established UAM airspace and interact with conventional IFR and VFR traffic in controlled airspace, resulting in making UAM operations operationally undesirable.

The safety analysis of the unmitigated collision risk between UAM flights shows that the unmitigated collision risk increases notably as the size of separation volume decreases. For example, if the separation standard is less than 1,500 ft horizontally and 150 ft vertically, the unmitigated collision risk increases to more than 20%, which is almost twice as high as the collision risk of 10% with 1,800 ft horizontal separation during the enroute flight phase. While the smaller separation standards can reduce the LoS and NMAC rate, it will considerably increase the unmitigated risk of collision between UAM flights. The tradeoff between operational suitability and safety (e.g., collision risk vs. LoS/NMAC rate) should be further investigated.

On the other hand, compared to the conflicts between UAM flights, there was significantly lower LoS and NMAC rate and unmitigated collision risk between UAM flights and conventional IFR/VFR flights if UAM flights stay within the UAM airspace construct, as the UAM airspace was designed to avoid existing IFR flight paths. The results show that UAM flights had more LoS/NMAC rate and collision risk with VFR aircraft than IFR aircraft. It is recommended that VFR aircraft operations should be considered in the design of the UAM airspace construct and separation standards.

Since the analysis in this paper is based on an open-loop unmitigated risk analysis, further mitigated fast-time simulation studies are required to evaluate the impact of mitigation of conflicts on the safety and operational suitability of UAM operations. Additional key safety metrics, such as the ratio of collision risk with maneuvering, to the ones without maneuvering for mitigating conflicts, need to be investigated to measure the effectiveness of reducing the occurrence of collision hazards, and to see if the separation volume can be further reduced with a set of candidate separation standards and various traffic scenarios.

The results also show that NMAC between UAM aircraft occurs during the departure/arrival phases at the vertiport airspace as much as during the enroute flight phase. Therefore, it is recommended that different separation minima and specific arrival/departure procedures should be applied for the separation at/around vertiport airspace. It is also recommended that a predeparture strategic conflict management needs to be developed and applied to minimize the likelihood of planned airborne conflicts between UAM operations and to reduce the deviation from the planned operational flight plan for tactical maneuvers to avoid the conflicts.

The route separation of 1,500 ft enforced in the UAM airspace construct limits the evaluation of various UAM traffic scenarios. In order to inform proper separation standards for UAM operations, additional Monte-Carlo and parametric fast-time simulation studies on separation standards using a risk-based approach are recommended, using a large set of representative UAM encounters to investigate encounter characteristics and associated collision risk. Further strategic and/or tactical conflict management studies are also recommended to evaluate the impact of multiple layers of conflict management on the safety of UAM operations, and to calculate the risk ratio of mitigated collision risk to unmitigated collision risk, with a set of candidate separation standards. Further research may help inform recommendations for performance-based separation standards for integration of UAM into the NAS. Additional subjective studies, such as human-in-the-loop evaluation, may be required to understand pilot and ATC acceptability and to validate the performance of candidate UAM separation standards. Analyzing and understanding conflicts between UAM aircraft and conflicts between UAM and other traditional traffic will allow for better design decisions in separation standards development and in airspace and route design activities.

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