

Collision Risk Modeling with Route Turns in Support of Urban Air Mobility Safe Separation

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Abstract—A wide variety of drones and advanced air mobility (AAM) aircraft manufacturers are planning near term operations within domestic airspace, possibly adjacent to traditional air traffic. One aspect of integrating new and existing traffic is to determine the safe separation of aircraft based on, among other parameters, communication, navigation and surveillance capabilities. Developing a collision risk model (CRM) appropriate to the applicable airspace and aircraft is a key factor in developing a safe separation. Leveraging previous work, a CRM has been adapted to analyze safe separation for a subcategory of AAM aircraft: electrical vertical takeoff and landing (eVTOL). In order to appropriately adapt the model for eVTOLs, it is important to incorporate applicable performance requirements and leverage available operational data. While data on actual eVTOL performance is sparse, several operational trials have been conducted on operationally similar aircraft which can be used to estimate their ability to adhere to a planned route of flight. While previous CRMs have largely considered straight flight segments to be representative of the entire trajectory, the trial data analysis suggests that assuming straight trajectories may not be a sufficient approach, especially with the smaller separation distances and curved paths envisioned for eVTOL operations. This CRM provides an initial examination of including turns within the modeling which would aid in presenting a more comprehensive picture of route separation.

Keywords—collision risk modeling, turning, route turns, eVTOL, UAM, AAM, separation minimum

I. INTRODUCTION

A key question for Urban Air Mobility (UAM) operations is whether parallel routes may be safely implemented in the constrained urban airspace environment, where there is little room for the airspace structure that is needed to provide both safety and efficiency. This paper provides an initial assessment of collision risk for eVTOL aircraft operating on parallel routes. While there are many factors that need to be considered for a full separation standard assessment, this work focuses on the impact of Required Navigation Performance (RNP) capabilities, available communication and surveillance infrastructure, and turns within routes. A comprehensive analysis will be required for the eventual development of eVTOL routes and Cooperative Areas [1].

Section II and III begin by providing a description of a collision risk model (CRM) [4]–[8] and outline the main assumptions. Section III includes route adherence data from airspace trials. Sections IV and V describe the modeling and the

basic geometry of including deviations when there is a turn in the route. Sections VI and VII discuss and summarize the results.

II. COLLISION RISK MODELING DESCRIPTION

CRM is a probabilistic modeling technique that determines the mathematical minimum safe separation of aircraft based on the associated requirements and operational procedures. Typically, CRM results are used, alongside underlying assumptions and operational insights, to help determine a feasible separation standard within an airspace planning paradigm. A separation standard ensures that aircraft operate with sufficient distance or time between them so that the risk of collision is below the level tolerable for an acceptable target level of safety (TLS). These standards are meant to govern the strategic management of the overall airspace [2]–[3].

Collision Avoidance (CA) systems [3]–[4] such as the Traffic Alert and Collision Avoidance System (TCAS) or Airborne Collision Avoidance System (ACAS), are not considered by the CRM or the subsequent separation standard. Those systems are reserved as a final safety control when all else fails. Relying on such to implement a separation standard indicates the airspace is inherently unsafe. This CRM, which focuses on the risks associated with normal operations [1], does not consider CA.

This CRM focuses on the risk of collision directly between two aircraft operating on parallel routes. It is derived by extending a model developed at the International Civil Aviation Organization (ICAO) [4] used for analyzing lateral separation in procedural airspace. This is shown in Fig. 1. In this work, the

$$CR = 2\Omega \frac{E\lambda_x}{d_x} P_z(0) \int_{\delta_s=-\sigma_s}^{\sigma_s} \sum_i \alpha_i \frac{1}{T_p} \int_{T_a=\tau_i+T_L}^{\tau_i+T_p+T_L} F dT_a f_S(\delta_s) d(\delta_s)$$

where $F = \iint_{V_1 V_2} \int_{\theta^*}^{\pi} f_{\theta}(\theta) \gamma(\theta, V_1, V_2, S) f_{V_1}(V_1) f_{V_2}(V_2) d\theta dV_1$

Fig. 1: ICAO CRM for parallel routes

model is adapted to be applicable to eVTOLs and is subsequently referred to as parallel separation.

III. MODELING ASSUMPTIONS

A. Scenario Overview

In the operational scenario being modeled, aircraft are in level flight on parallel routes with turns, with each route populated at a given overall traffic density. An aircraft on one of the parallel routes erroneously deviates from course, as depicted in Fig. 2.

The probability that this deviation leads to a collision is calculated using the following operational assumptions:

- Aircraft are flying in the same direction and at the same altitude
- Aircraft are operating at comparable speeds
- Aircraft are adhering to their routes with a given navigational accuracy
- Aircraft are free of conflict for a given period of time prior to the deviation

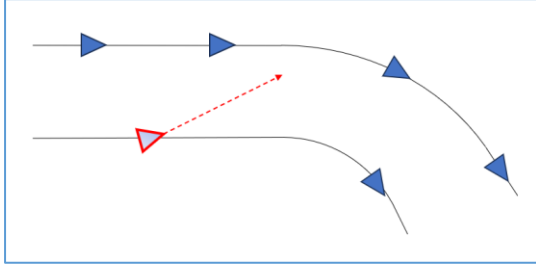


Fig. 2: Depiction of 2 parallel routes with turns.

Based on this, there are several quantified assumptions made about certain requirements and parameters of the aircraft operation, as described in the sections below.

B. Aircraft Capability Assumptions

A survey ofBased on publicly available information from various eVTOL manufacturers, we make the assumption that the maximum typical operating airspeed is 120 kts, and the aircraft have a rough diameter of 50 ft. Since a higher operating speed yields a higher risk from the CRM, a range of speeds centered on this operating speed is used.

The CRM also considers a value for the blunder or deviation rate of aircraft, defined as the likelihood of an aircraft carrying out an unplanned divergence from its planned route. While there remains much uncertainty around the performance characteristics of eVTOL aircraft and airspace operations, there are many airspaces that have been operating for decades and have plentiful data available. Several studies of deviation rates of commercial aircraft have been published for both oceanic as well as parallel terminal approaches. Relatedly, several oversight organizations have reported on their rates of loss of separation. Nearly all these studies and reports find a rate on the order of 1×10^{-5} deviations per operation. Therefore, this is deemed a suitable deviation rate for the initial analysis of eVTOL operations.[9]-[13]

It is also necessary to define the magnitude of the deviation angle. Based on a study of 6 years of North Atlantic traffic, the mean deviation angle was found to be 16° . A probability distribution has been employed centered about this mean and is used in the modeling herein. As this data pertains to large commercial passenger aircraft, a similar study will need to be carried out for eVTOLs.

C. Separation Provision Intervention Capability Assumptions

A key input to the CRM is the timing associated with how long it takes for a conflict to be intervened with and resolved. ICAO defines the Separation Provision Intervention capability (or simply, intervention capability) as the humans and systems used to detect and solve a conflict; and, to implement and monitor the solution [4]. A model for the intervention capability is depicted by the activity diagram shown in Fig. 3, where the controller and/or the pilot may be involved in the detection of

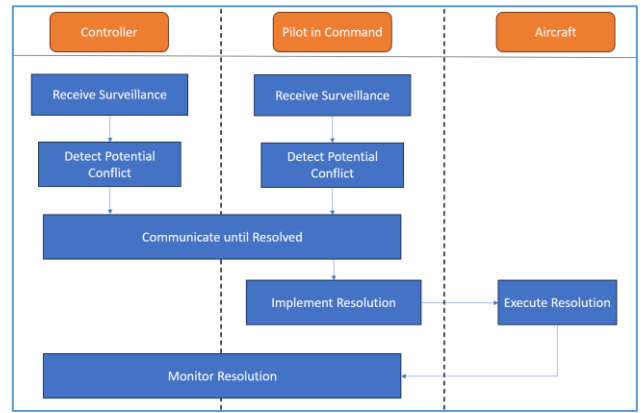


Fig. 3: Intervention Capability Model.

the conflict.

The communications time for the controlled UAM operation is modeled as the sum of six sequential parts:

- 1) Time for controller to detect conflict, or to recognize an incoming message from pilot
- 2) Time duration of the first transmission from controller to pilot
- 3) Time for pilot to notice controller's transmission
- 4) Time duration for pilot to acknowledge transmission
- 5) Time duration of a second transmission from controller to pilot, containing the maneuver instruction
- 6) Time duration for pilot to acknowledge instruction

The total communications time T_C is depicted in the sequence diagram shown in Fig. 4, with each time interval labeled as in the enumeration above.



Fig. 4: Push to Talk Communications Model.

The time it takes from detecting the deviation to the aircraft executing a resolution will be analyzed as the sum of three parts: surveillance latency, communications time, and execution time.

The surveillance source assumed for this operational environment is ground-based ADS-B with an update of 3 s 95% of the time.

In some airspaces, there are Required Communication Performance (RCP) standards [15] for communication technology capabilities. Currently, the typical controller-pilot communication in domestic airspace, commonly referred to as “push-to-talk”, does not have an associated RCP. However, this system has been in use for decades and there is a large amount of operational data available. Leveraging frequently-cited data that has been previously collected and analyzed in several fundamental studies by Cardosi, et. al., [18]-[21] a probability distribution of the communication time is developed to reflect a typical intervention response. Combining all the data from the different studies, the distribution in times that represent the 6 steps outlined above ranges from about 20 s 5% to 60 s 95% of the time.

The time it takes for an aircraft to execute the maneuver to avoid a loss of separation or collision needs to be considered. Chen 2010 [22] provided simulated maneuver timing responses both for climbing and turning aircraft. The paper notes a minimum of 50 s, a mean of 100 s and a maximum of 200 s. These values are consistent with what has previously been assumed by ICAO for oceanic traffic, which is 75 s, or the amount of time it takes an aircraft traveling at 480 kts to climb 1000 ft. Note that both of these references are regarding commercial aircraft. It is expected that eVTOLs will have a lower execution time; however, data needs to be collected on this operational aspect.

Combining all these elements, the resultant intervention timing model is provided in Table 1. As with many aspects of CRM, a conservative approach is applied to buffer the risk estimate. As such, note that the longer intervention times are unlikely but still must be accounted for within the nominal operations.

Table 1: Intervention timing model developed for this application.

<i>Intervention and Maneuver Time</i>	<i>Cumulative Percent</i>
30 (s)	50%
40 (s)	75%
54 (s)	90%
64 (s)	95%
89 (s)	99%
120 (s)	100%

D. Navigation Assumptions

In order to qualify for certain procedures in various airspaces, commercial aircraft are often certified to specific Required Navigation Performance (RNP) levels, which specify bounds on the maximum horizontal distance that an aircraft can be from a defined centerline. Several eVTOL manufacturers have indicated an intent to certify their aircraft to RNP 0.3, which would require that the Total System Error (TSE) of an aircraft’s lateral distance from centerline be within +/- 0.3 NM for 95 % and within +/- 0.6 NM for 0.00001 % of the flight time [14].

In the absence of sufficient eVTOL performance measurements that would confirm operational compliance with RNP 0.3, the actual performance that can be expected of these aircraft is suggested by several helicopter trials. To establish the navigation assumptions used in the CRM, the results of two studies were considered. While these studies are consistent with an RNP 0.3 assumption, they also indicate a degradation in performance during turns. Therefore, this CRM will assume RNP 0.3 navigation performance, and will include turn modeling. The two studies supporting these assumptions are briefly described below, as well as anecdotal evidence from early eVTOL trials.

“Actual Navigation Performance of Helicopters in the Final Approach Phase of RNAV (GPS) Approaches” from Thiel et al in 2013 [16] provides data from test flights of helicopters using independent high precision differential GPS to determine horizontal and vertical deviations from the planned route during the final approach phase. While the horizontal navigational error increases as the aircraft is further from the FATO, the worst case observation showed a cross-track error of 0.034 NM with a standard deviation of 31.73 m, which is well below RNP 0.3 performance requirements

Troller 2016 [17] provides data and analysis from helicopters flying along the Swiss Low-Flight Network to support the development of an RNP lower than RNP 0.3. Over 24 flights were flown along increasingly challenging routes, and data was collected and analyzed for centerline adherence. Analysis showed that performance was typically well below 0.1 NM, with deviations of up to 0.6 NM on the more challenging routes with tighter turns, suggesting that care should be taken in choosing operationally relevant turn definitions.

Anecdotally, there is general acknowledgement in the eVTOL manufacturer community that navigation performance consistent with RNP 0.3 is achievable. Indeed, unpublished

results from eVTOL trials which took place under the supervision of Airways New Zealand in 2021 and 2022 provides further evidence for horizontal route adherence. The track keeping errors from both trials were well within the RNP 0.3 bounds.

E. Turn Modeling Assumptions

With few exceptions, parallel separation standards for oceanic and remote areas tend to be large and typically apply to routing that extends for long distances; hence, turns within the routes have not previously been considered within the CRM. Turns were accommodated by the separation minimum in only one case that could be identified, where an initial assessment of 5 NM separation rules found the separation needed to increase to 7 or 8 NM once turns were taken into account [12].

Routes for eVTOL traffic are anticipated to be much shorter in distance, much closer in separation, and to incorporate multiple turns to maneuver the airspace. As described in the previous section, an aircraft's compliance with RNP requirements lessened when flying through turns in the route; so, incorporating parallel turns within the model is deemed to be important.

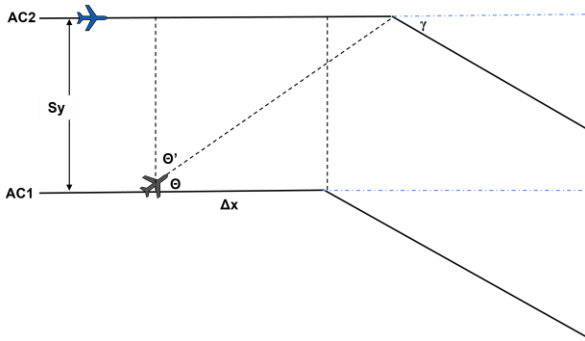


Fig. 5: Depiction of 2 parallel routes with a γ degree turn.

To include this within the CRM, some specifics of the geometry were analyzed. Fig. 5 provides a diagram of two aircraft traveling along parallel routes that have a heading change of γ degrees, prior to which the deviating aircraft deviates towards the opposite track. For a certain Δx , there is a deviation angle Θ which marks the transition from the aircraft intersecting the parallel portion of the route to the aircraft intersecting the turn portion of the route. For angles greater than Θ (denoted as Θ' in Fig. 5), the parallel model would suffice for separation calculation. For angles 0 to Θ , a modified parallel model is required to capture the different geometry for the turn part of the route.

Fig. 6 provides another view of the geometry with a deviation specifically angled toward the turn portion of the route. This highlights the fact that, due to intersecting with the turn in the route, the collision time and distance for the deviating aircraft is now much less than it would be for a parallel time and distance. The amount of distance less can be calculated with basic geometry and is denoted by 'dc'. The effective reduction in the parallel spacing can also be determined similarly and is denoted by 's'.

F. Traffic Density

The density of traffic on the routes impacts the likelihood that the blunder results in a collision geometry. While traffic density can be modeled in many ways, in this model we apply the concept of occupancy, which is a measure of airspace density that is used by global monitoring groups. The application of the occupancy term in this model assumes very dense airspace with aircraft spaced close to the governing

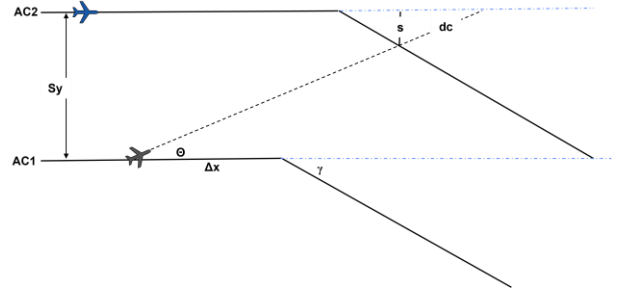


Fig. 6: Depiction of parallel turns with the bottom aircraft deviating toward the top route with a turn.

separation minimum.

IV. CRM RESULTS

The CRM adopted for this application is based on the modeling assumptions described above, and an estimation of the probability given by the expression,

$$\Pr(A) \Pr(B|A) \Pr(C|AB)$$

where A, B, and C are the following events:

- A: Aircraft deviates from route
- B: Intervention Capability is insufficient
- C: Aircraft geometries result in a collision

The probability of aircraft deviation is provided in section III.B. The probability that intervention is insufficient is primarily a function of the intervention time available, which in

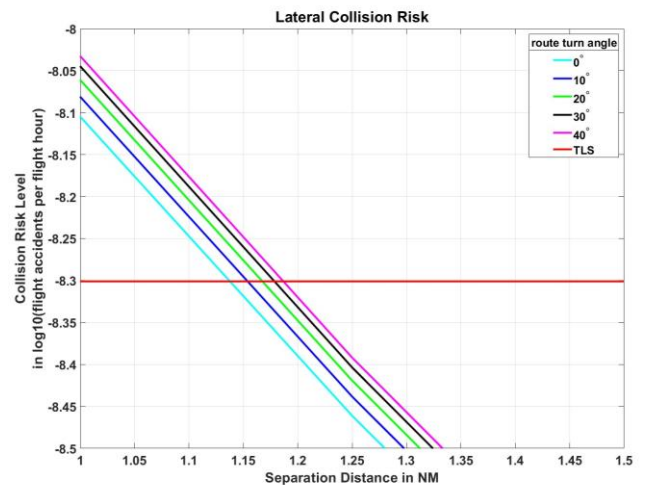


Fig. 7: Results of the CRM using the parameter values herein.

turn is impacted by numerous modeling assumptions. Similarly, the probability that the aircraft positions result in a collision is a function of multiple modeling assumptions, including navigation assumptions and traffic density.

The resultant collision risk is calculated for a range of route turn angles and then compared to a Target Level of Safety (TLS) that is commensurate with existing aviation safety standards, to obtain a minimum safe separation distance as shown in Fig. 7. The safe separation distances between tracks are in the range of 1.1 to 1.2 NM, and the size of the turn does have a small but significant impact. As a measure of confidence, a rough guideline of 4 times the RNP value is often applied as an estimation for safe separation, which is consistent with the results.

V. DISCUSSION

The primary question of whether turns in the parallel routes might impact the separation between the routes is largely answered in the affirmative, in that there is a clear impact for different values of the heading change suggesting that further investigation is warranted. As is often the case, one development revealed the necessary inclusion of several additional components and other next steps.

The base model is a CRM developed for oceanic and remote airspace where the separation distances are much greater and where a simplifying assumption was made to only consider the navigation errors (RNP, speed errors, etc.) for one of the two aircraft in conflict. Given the shorter times and distances expected for eVTOL, some of the initial next steps will be to model these errors for both aircraft.

Obtaining operational insight toward the intervention timing model is critical. As there is no RCP standard governing these times, a model was created using available data. If there are adjustments to be made based on implementation experience, it could have a significant impact to the results.

Refining the speed model toward eVTOLs specifically may be useful as well. While they are en route, they are expected to be in a certain flight mode where a minimum speed would need to be maintained to ensure fixed wing flight. Reducing the variability in the speed could also affect the outcome.

Many of the other assumptions noted above, such as the deviation rate and angle are also based on commercial aircraft. It will be critical to capture data for all aspects of eVTOL operation such that the CRM can continue to evolve toward accurately representing the operational paradigm of eVTOLs.

Finally, the work described here provides a calculated separation minimum. This is only one piece of creating an operational separation standard. It is critical for the assumptions and result to be vetted by operational and implementation personnel. Human factors elements need to be assessed and included. This often results in an additional distance buffer being added to the mathematical separation.

Beyond the operational paradigm described here, the UAM industry is expected to mature toward uncrewed aircraft, automated control and other systems that are not in widespread

use today. Capturing the expected timing and interactions of such systems is key toward evolving the CRM appropriately.

VI. SUMMARY

This paper provides a basic initial step toward applying traditional CRM techniques to emerging operations like UAM. Besides modifying assumptions to be applicable to the UAM environment, the parallel CRM modeling was also updated to include turns, a key development needed for implementing shorter eVTOL routes which may contain several turns within relatively shorter distances. The results show a dependency on turn geometries and suggest deeper investigations for next steps.

In addition, a definitive set of modeling parameters were identified and quantified with preliminary data, enumerated below:

- Max operating airspeed
- Aircraft diameter
- Deviation rate
- Max deviation angle
- Surveillance latency
- Separation Provision Intervention time
- Aircraft maneuver response time
- Total System Error for lateral position
- Track heading change
- Traffic density

Next steps will involve refining and expanding this set of modeling parameters, leveraging measured data wherever possible, and expanding the set of operational conditions under which the risk of collision is evaluated.

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