Effectiveness of Preflight Deconfliction in High-Density UAS Operations

Peter Sachs, Chris Dienes, PhD., Erin Dienes, PhD., and Maxim Egorov, PhD.

Report TR-009
October 3, 2018

Table of Contents

1. Introduction

In a future high-density airspace environment with most unmanned aerial vehicles operating autonomously, what separation minima should we use to ensure safe and efficient operations? Can two vehicles fly closer to one another if they both have precision navigation equipment? Can dynamically created preferential routes, or corridors, improve safety without compromising efficiency targets? Altiscope envisions using our open risk framework to help answer these questions by applying separation standards between different unmanned aerial vehicles (UAVs) depending on underlying risk factors.

This is the first of several studies of separation methods to help inform the risk framework's modeling assumptions. While this report focuses on the effectiveness of preflight deconfliction techniques, future reports will explore how tactical and capacity management strategies might help resolving traffic conflicts.

In high-density environments, we find that loss of separation events increase linearly with the effective flight rate. And while preflight deconfliction techniques decreased the loss of separation rates, they also decreased the effective flight rate in a region. Even at the lowest volumes, we observed losses of separation occurring at rates about four orders of magnitude more frequently than occur in today's airspace.

Therefore, to achieve safe airspace usage, regardless of separation criteria, we need to apply a greater set of tools to managing flights, just like air traffic controllers do today. Relying only on simple preflight deconfliction rules and allowing flights to operate without having to use traditional airspace structures (e.g. altitude separation, one-way routes or charted arrival procedures) simply does not provide a path to safe airspace usage. In that regard, the findings of this report are consistent with Altiscope's earlier analysis of dense airspace dynamics. (Golding, 2018)

2. Study Design and Assumptions

We used Altiscope's UTM prototype and airspace simulator to model 16 different scenarios. The scenarios are different combinations of flights per hour and airspace regions. We ran the studies at 100, 250, 500 and 1,000 flights per hour. The four regions, each 10 nautical miles (18.5km) on a side, are:

- Uniform: Flights takeoff and land at points distributed randomly throughout the airspace.

- Gaussian: Flights are concentrated at one node at the center of the region, with the likelihood of a flight originating at a location decreasing with the distance from that point.
- Bimodal: Two Gaussian-distributed nodes with their centers 5km apart (Figure 1).
- Shenzhen: We used publicly available population data to create a simple, scaled model representing the Shenzhen, China region, which has some extremely dense neighborhoods and some very sparsely populated areas within short distances of each other (Figure 2).

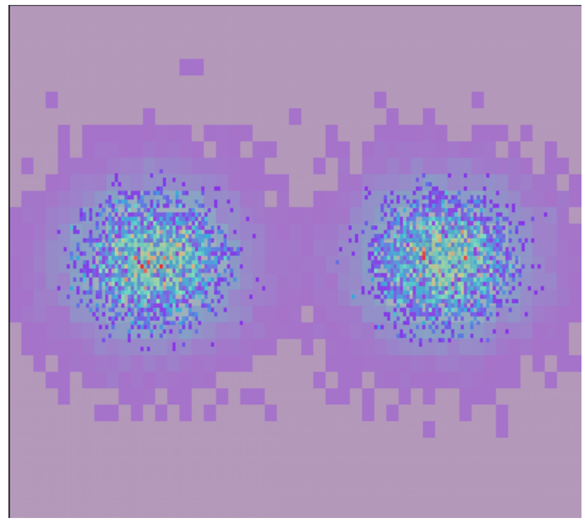

Figure 1: Vehicle start locations in the bimodal region. Yellow and green areas have the most flights, while purple areas have the least flights.

We make several assumptions to simplify the modeling of our simulated airspace. In all scenarios, vehicles have identical performance characteristics: they have relatively short

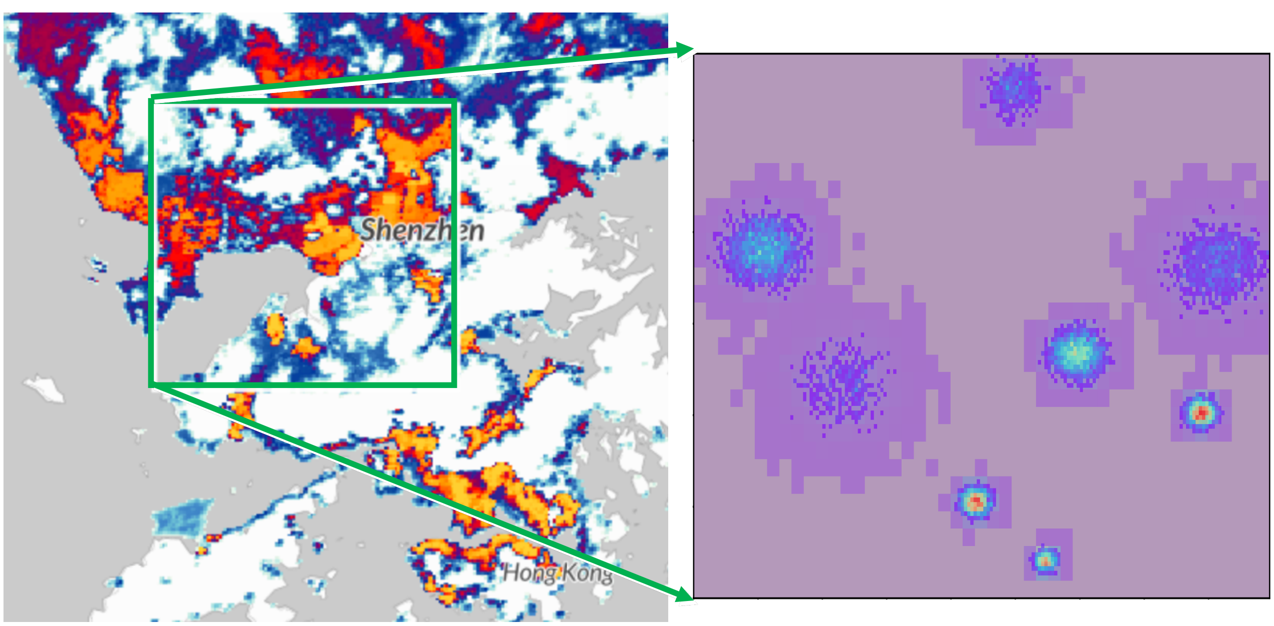

Figure 2: The population density map at left was used to construct the simplified airspace region at right. In the simulated airspace, the most takeoffs occur in the red areas, and least occur in the purple areas. (Source: luminocity3d.org)

vertical takeoff and landing (VTOL) ascent and descent phases; they cruise at 20m/s (39 knots); and they are 10m (33ft) across, which is about the size of an urban air mobility vehicle like the Airbus Vahana. Also, all vehicles cruise at the same altitude, and there is no vertical deconfliction between them.

3. Preflight Deconfliction and Filing Service

In these studies, the only opportunity for deconfliction occurs when the simulator generates a flight plan. At that point, a few seconds before departure, the planner looks at all other flights that it expects to be in the air (i.e. previously filed flight plans) and, based on their predicted positions at each one-second interval, modifies the new flight plan's horizontal routing around any traffic conflicts. Its goal is to maintain at least 500 feet between all vehicles. Compared with today's air traffic control strategies, this is intentionally simplistic: there is no provision in this study for vertical separation, speed control or routing along one-way airways to reduce the number of conflicts. There is also no time-based metering system in place, which helps provide order and predictability in today's airspace.

The simulator's planner performs horizontal deconfliction as it receives flight plans using a geometric path planning methodology to perform deconfliction based on (Aljarboua, 2009). The advantage of this approach is that is computationally efficient. The tradeoff is that revised routes may not be efficient, and a change of course may actually prolong the conflict between two

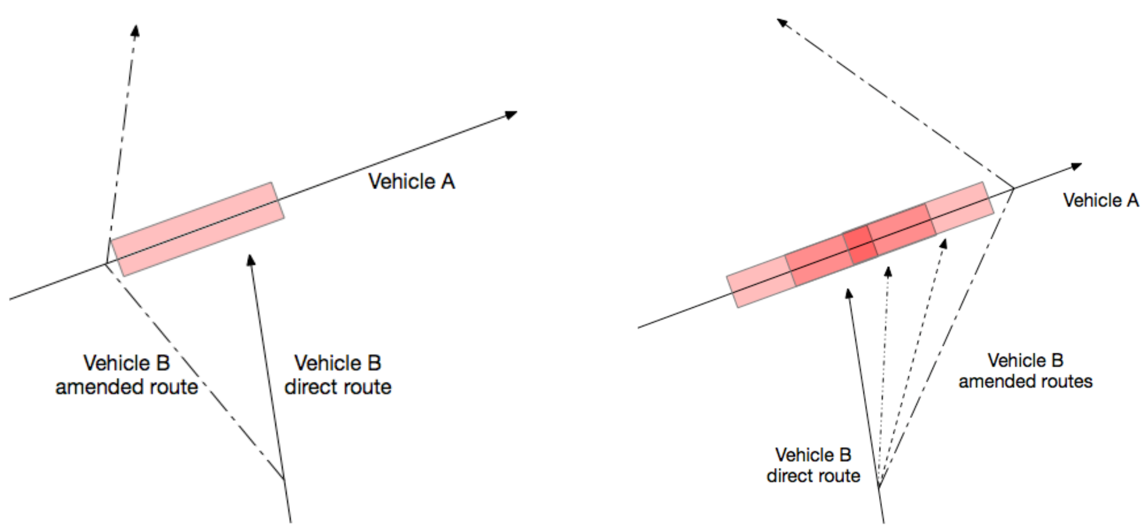

Figure 3: Preflight deconfliction treats the location of a conflict between two vehicles as a "no-fly zone" for the second vehicle. The size of the area to avoid is a function of the minimum separation the planner has been instructed to maintain, plus a buffer zone. At left, a fairly effective resolution serendipitously has Vehicle B pass behind Vehicle A. At right, the planner deconflicts in the other direction, and must revise the route several times to overcome the convergence of the two vehicles.

vehicles. The planner checks the route for conflicts in continuous time based on the flight plans and routes that it has already approved. When it detects a conflict between vehicles, it tries to adjust the route of the vehicle not yet airborne. It will add a path segment either to the left or right of the region in which it expects the first vehicle to be flying, but it is blind to that vehicle's direction of travel. As a result, it may choose the less-optimal solution of turning to fly ahead of and in front of the first vehicle. Having successfully generated a new path segment around the conflicting vehicle, it repeats these steps all the way to the destination. However, there is no guarantee of a conflict-free route, especially in instances with many vehicles in conflict with each other, or difficult-to-resolve encounters at shallow convergence angles.

In this study, we also tested the effectiveness of a flight plan filing service, which double-checks each route before approving the flight, in the seconds before departure. The filing service does not make any changes to routes, but is able to detect if a new flight plan will conflict with a previously approved route. In those cases, it denies the flight plan, preventing it from departing. We tested the filing service both as a standalone function (no other deconfliction applied), and in conjunction with the preflight deconfliction algorithm. In the latter instance, the filing service acts as a second check on the deconfliction algorithm's work. This is particularly useful when the deconfliction algorithm was unable to resolve all conflicts along a flight's route. When this occurs, the filing service is able to catch those plans that are not properly deconflicted and reject them.

To establish a baseline point of comparison, we also ran all of the scenarios described above with no deconfliction at all. In other words, the probability of an encounter is left to chance, as every vehicle flies directly from its origin to destination.

The combination of four flight rates, four different regions, and four airspace management strategies (including the baseline without any form of deconfliction or conflict check) yielded 64 unique configurations. To ensure statistical significance of pairwise loss of separation rate comparisons, we ran each of the 64 configurations for 120 hours. The combined simulator run time was 7,680 hours, or the equivalent of 320 days.

4. Measurements

To evaluate each scenario, we look to a combination of safety metrics and efficiency metrics. An optimized set of airspace rules allows high utilization (i.e. a large number of flights) with a minimum number of rejected flight plans and routes that add as little extra distance as possible compared to a direct route. Additionally, rates of loss of separation, collisions and near-midair proximity events should be minimized. For this study, we arbitrary set the minimum separation distance between all vehicles at 500 feet (152m) laterally. Again, by design, there was no provision for vertical separation, nor does the deconfliction algorithm take advantage of other tools that air traffic controllers use today, like course divergence, pilot-provided visual separation, or passing-and-diverging rules. We chose 500 feet because it allows vehicles to operate much closer than they can today. This is substantially less than the 2,000-foot (610m) recommended minimum separation distance between a small UAV and a manned aircraft, as calculated by the EXCOM SARP in 2017. We feel this is a reasonable goal for minimum separation between autonomous UAVs in the future, on the assumption that all vehicles meet some set of minimum performance and communications requirements. The simulator's analysis script counts each instance of a loss of separation and normalizes that to a rate per flight hour. As a loose proxy for the Airprox A+B ICAO metric, we also count those loss of separation events in which 25 percent or less of the required separation was maintained. Any proximity event of less than 10m is counted as a collision (recall that each vehicle has a diameter of 10m, and therefore a radius of 5m).

5. Findings

The table on Page 6 summarizes the safety event rates per flight hour for all scenarios. Tukey's multiple comparison adjustment factor was used to construct an assortment of pairwise confidence intervals which were used to compare competing deconfliction methods (see Annex A). The method provides a simultaneous 99% confidence for all intervals for a given deconfliction comparison and a particular rate of event. In general:

- Safety event rates for preflight deconfliction alone tend to be significantly less than baseline,
- Rates for the filing service alone tend to be significantly less than preflight deconfliction alone,
- Rates for when both preflight deconfliction and the filing service were enabled tend to be significantly less than scenarios with only one of those tools applied.
- Collision results at low traffic volumes were not statistically significant because of the small number of events observed.

We used Poisson regression models to investigate the impacts of deconfliction methods given the presence of the confounding effect of reduced effective flights per hour. The same (significant) order of event rates was present when making adjustments for decreased effective flight volumes. Additionally, we constructed plots describing the magnitude of the effects for each of the model variables. In some cases the effects of a deconfliction method exceeded the effects of observed flight volume differences; while in other cases they did not.

The lowest observed loss of separation rate across all scenarios was 3.46e-1 per flight hour, at 100 flights per hour in the uniform region with both the filing service and preflight deconfliction enabled. At 500 and 1,000 flights per hour, loss of separation rates of between 1.57 and 6.822 per flight hour were more typical, except in the baseline scenarios with no deconfliction used.

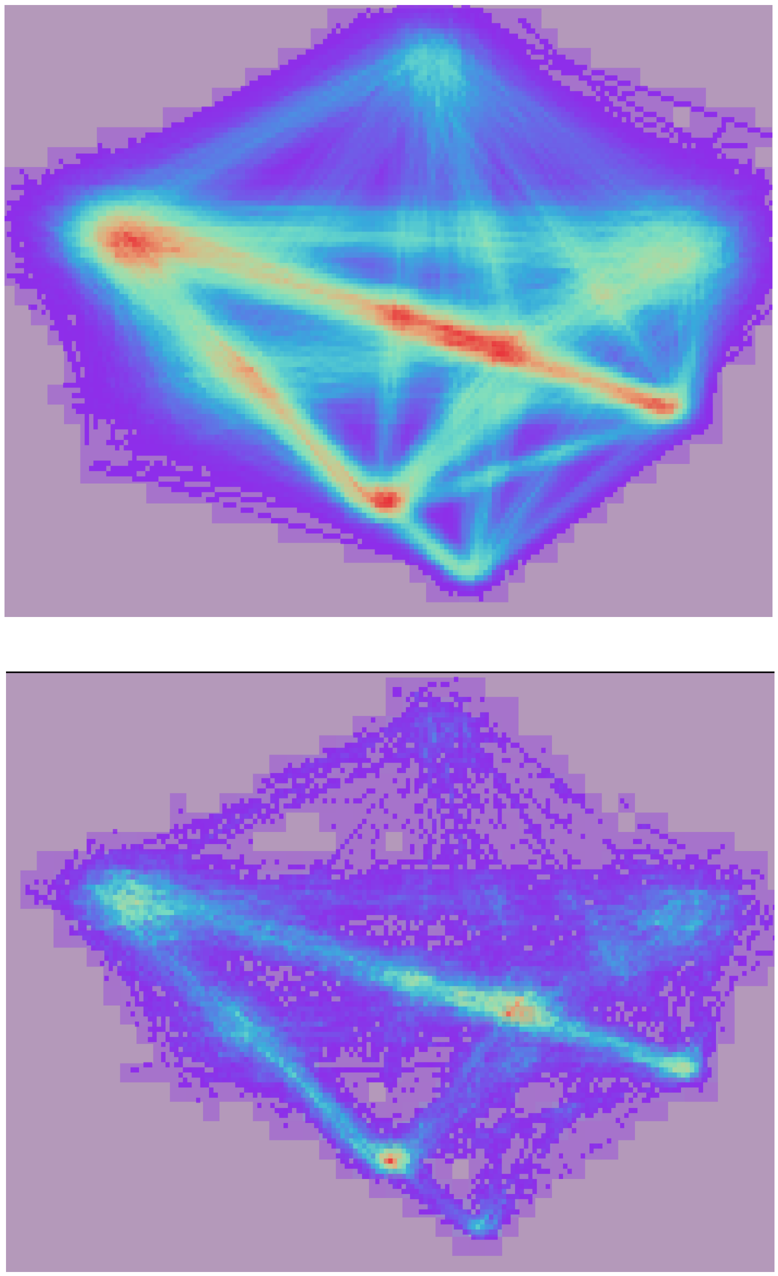

Figure 3: The Shenzhen region at 1,000 flights per hour. The plot at top shows where the most flights operated (orange and red regions), while the plot at bottom shows where the most loss of separation events occurred (green and orange regions) when no preflight airspace management tools were applied.

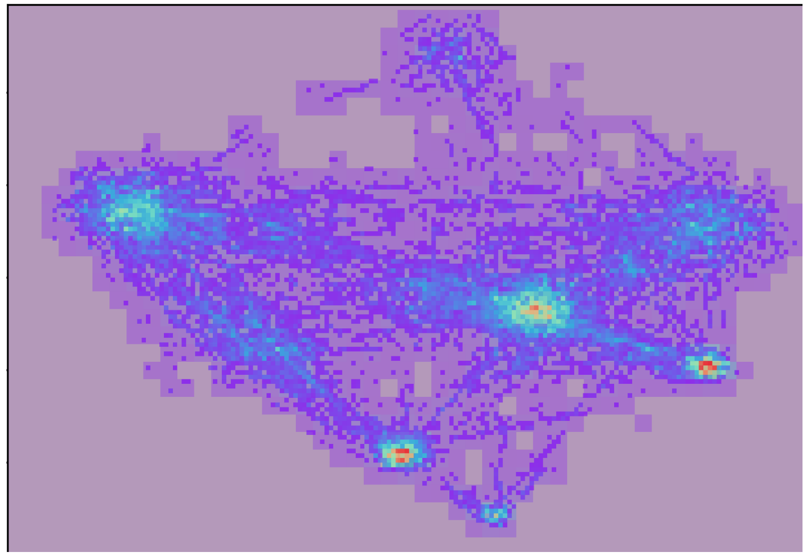

Figure 4: In the Shenzhen region at 1,000 flights per hour, preflight deconfliction reduced the number of loss of separation events in areas between high-density takeoff and landing nodes.

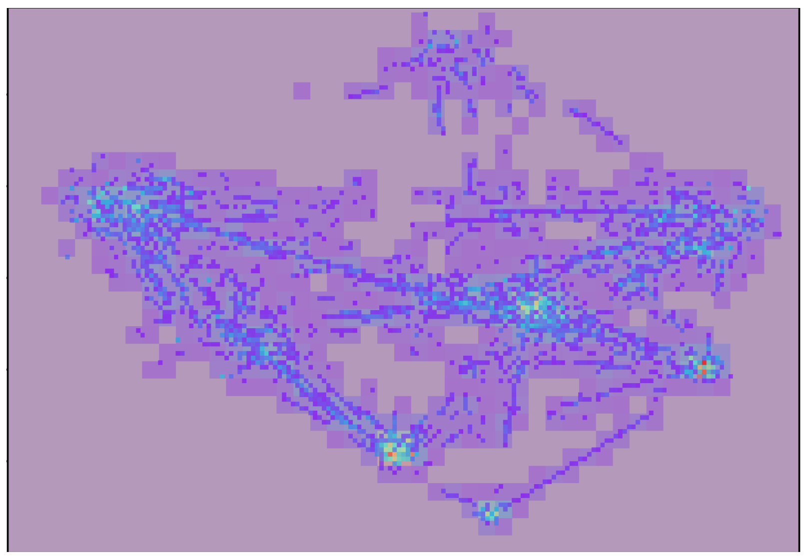

Figure 5: The filing service alone was more effective than preflight deconfliction alone at reducing losses of separation across the Shenzhen region.

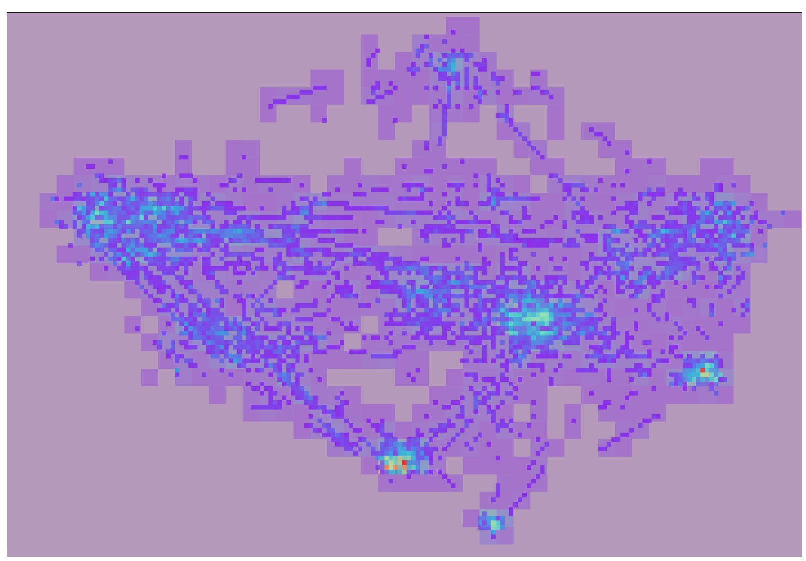

Figure 6: The effectiveness of the filing service combined with preflight deconfliction is less apparent, even though the actual rates were lower in a statistically significant way.

	No Deconfliction				Preflight Deconfliction				Filing Service				Filing Service and Preflight Deconfliction			
Loss of Separation Rate per Flight Hour																
Region	**100**	**250**	**500**	**1000**	**100**	**250**	**500**	**1000**	**100**	**250**	**500**	**1000**	**100**	**250**	**500**	**1000**
Uniform	0.744	1.869	3.694	7.416	0.550	1.430	2.778	4.786	0.441	0.952	1.664	2.552	0.346	0.749	1.238	1.849
Gaussian	1.257	3.126	6.180	12.369	0.863	2.014	3.961	6.531	0.493	1.131	1.958	2.934	0.461	0.951	1.570	2.296
Shenzhen	1.346	3.499	7.060	14.010	0.752	1.834	3.337	5.278	0.482	1.040	1.713	2.548	0.383	0.778	1.241	1.826
Bimodal	1.936	4.735	9.552	19.182	1.011	2.449	4.464	6.822	0.554	1.218	1.947	2.719	0.427	0.949	1.421	2.071
Airprox A+B Rate per Flight Hour																
Uniform	0.156	0.403	0.786	1.586	0.118	0.295	0.592	1.015	0.100	0.208	0.356	0.537	0.079	0.142	0.261	0.376
Gaussian	0.245	0.573	1.128	2.313	0.147	0.353	0.711	1.220	0.086	0.213	0.370	0.562	0.070	0.176	0.276	0.413
Shenzhen	0.266	0.672	1.309	2.630	0.119	0.317	0.599	0.942	0.069	0.184	0.299	0.456	0.070	0.119	0.198	0.292
Bimodal	0.405	0.918	1.860	3.734	0.165	0.424	0.820	1.253	0.089	0.208	0.346	0.479	0.064	0.172	0.239	0.330
Collision Rate per Flight Hour																
Uniform	0.003	0.014	0.034	0.073	0.005	0.012	0.028	0.047	0.007	0.005	0.013	0.025	0.004	0.006	0.012	0.018
Gaussian	0.005	0.018	0.048	0.100	0.007	0.019	0.032	0.058	0.004	0.014	0.014	0.027	0.003	0.005	0.016	0.020
Shenzhen	0.007	0.022	0.054	0.106	0.005	0.014	0.027	0.044	0.004	0.007	0.015	0.025	0.006	0.005	0.008	0.015
Bimodal	0.014	0.038	0.079	0.154	0.009	0.026	0.048	0.067	0.004	0.011	0.020	0.030	0.003	0.008	0.010	0.020

Table 1: Loss of separation, Airprox A+B and Collision rates per flight hour.

The table on the previous page does not indicate effective flights per hour. Particularly in the 500- and 1,000-flight-per-hour scenarios with at least one tool enabled, the effective flight-per-hour rate was between three-quarters and half (and sometimes even less) of what was expected. This large reduction caused us to further investigate whether the drop-off in safety event rates was really a function of the tools being used, and not just a side effect of the lower rate of vehicles flying, since so many flight plans were rejected.

Our first attempt at this was simply to plot loss of separation rates against the effective flights per hour in each scenario. This yielded the following charts, one for each simulated airspace region (Annex A, Figures 7-10). In each chart, the black lines are baseline scenarios with no airspace management method, so no flights are rejected. As expected, the loss of separation rates are highest. The three combinations of airspace management methods performed consistently in all four regions, with preflight deconfliction alone (orange lines) having the least effect in reducing loss of separation rates, based on the change in slope. A combined approach that used both preflight deconfliction and the filing service (green lines) had the greatest effect in reducing loss of separation rates. Except at the lowest flight volumes, the filing service alone (blue line) cut the effective flight rate roughly in half, providing an indication of the number of conflicts in a region. In the bimodal and Shenzhen regions, the reduction was even greater, as the complex airspace resulted in very concentrated areas of flights and, therefore, elevated safety event rates in those areas.

To further tease out the effects of airspace management strategies when there was so much variation in effective flights per hour, we used a Poisson regression model to calculate pairwise ratios of safety event rates. This approach controls for region and effective flight volume, as shown in Table 2. The intervals are significant in all but one case (Collision rates when no deconfliction is used, versus preflight deconfliction). To construct the below intervals we used a 99% Bonferroni corrected confidence interval to account for the multiple comparisons.

The values in Table 2 should be read as percentage changes in event rates between airspace management methods. For instance, from the upper-left cell, loss of separation rates when preflight deconfliction is used are about 84 percent of the rates when no deconfliction is applied. In other words, this is a reduction of about 16 percent. Thus, the most remarkable result, as seen in the far-right column, is in airspace in which both preflight deconfliction and the filing service are enabled. These tools reduce losses of separation by about 61 percent, and reduce severe Airprox A+B events by about 65 percent compared with unmanaged airspace.

	99% CIs for ratio of event rates across deconfliction method			
	$\lambda^{pre} \div \lambda^{none}$	$\lambda^{filing} \div \lambda^{pre}$	$\lambda^{filing+pre} \div \lambda^{filing}$	$\lambda^{filing+pre} \div \lambda^{none}$
Loss of Separation	(0.832, 0.844)	(0.601, 0.613)	(0.749, 0.770)	(0.382, 0.391)
Airprox A+B	(0.805, 0.831)	(0.599, 0.627)	(0.692, 0.737)	(0.348, 0.368)
Collision	(0.912, 1.066)	(0.567, 0.699)	(0.618, 0.820)	(0.387, 0.505)

Table 2: Pairwise ratios of safety event rates in various deconfliction schemes, controlling for region and effective flights per hour.

6. Conclusions and Future Work

We deliberately excluded several other methods of separation from this study, because we needed an overly simplistic starting point to begin understanding complex airspace and vehicle interactions. Human controllers have a variety of tools for maintaining separation, depending on the scenario: vectoring, altitude assignments, speed restrictions and course divergence, among others. This study considered only the first of those, but with the condition that all conflict resolution be provided before each flight departs. This would be analogous to a human controller sitting down in the control tower or in front of a radar scope at the start of each shift with a roster of all flights for the next several hours, with the expectation that she provide separation instructions to all aircraft in advance.

We are unable to say from this study whether the 500-foot minimum separation distance between vehicles can be safely met, since we did not consider variations in vehicle performance characteristics. In other simulations, we found that larger separation distances resulted in higher loss of separation rates, especially without a filing service to limit the overall number of vehicles and conflicts. We think that the 500-foot minimum separation value is still useful for our studies, since it enables us to test airspace density values much higher than we see today. It is 36 times closer than the standard 3 nautical mile minimum separation between aircraft in most terminal airspace today, and about 12 times closer than the 1-mile separation allowed between closely spaced parallel ILS arrivals in the United States.[1]

In studying four different airspace regions with varying levels of complexity, we can see that the preflight airspace management tools we tested function similarly across those airspaces.

---

[1] Controllers sequencing arrivals to parallel runways that are less than 2,500 feet apart can take advantage of the provisions of FAA JO7110.308C, which allows a “pair” of arrivals to be as little as 1 nautical mile apart (diagonal distance). The order requires additional controller training and safety event reporting, and is dependent on local weather conditions. Controllers must apply Wake Recat separation minima as well, which affects spacing between pairs of arrivals.

While that may not hold true to any conceivable airspace, the consistent levels of effectiveness provide a reasonable guide to gauging their usefulness. In increasingly complex airspace (Bimodal and Shenzhen), the filing service, alone or combined with preflight deconfliction, reduced losses of separation by a greater degree than in simpler airspace. But that also meant that in complex airspace, a greater proportion of flights were rejected than in simpler airspace. With additional refinement, the filing service in particular may be a useful check after other preflight route and schedule adjustments are made. Thus, it would be able to catch the handful of flight requests that pose too much of a strain on the airspace, either because of their routing, the airspace capacity or other vehicle characteristics.

In the UTM (unmanned traffic management) realm, these results point to the effectiveness we might expect for architectures that rely only on preflight airspace reservations to manage multiple flights in a region. While this approach may be sufficient at very low traffic volumes, we see that even at only 100 flights per hour in a region about the size of the city of Frankfurt, loss of separation rates are 10,000 times higher than what we see today. Airprox A+B safety events happen roughly once every 2 to 5 flight hours in our scenarios, a startlingly high rate for such severe events. By comparison, both the U.S. Federal Aviation Administration and EUROCONTROL reported actual Airprox A+B (or equivalent metric) rates of between 5 and 10 events per million flight hours since 2015 (Sachs, 2018). In other words, these serious safety events are occurring about 100,000 times more frequently in our simulations than in the real world.

Combined approaches, using both preflight deconfliction and a filing service to check for further conflicts, were very effective at lowering safety event rates – but the underlying rates we observed remained in the same order of magnitude. This will likely be unacceptable for regulators or the general public.

Furthermore, achieving those reductions in the 100-square-mile regions we tested required blocking more than half of flights from departing. That poses a significant constraint that means our airspace, regardless of exact location or dynamics, will be unable to accommodate a large amount of the projected demand without additional strategies to safely manage that traffic.

Therefore, our next set of studies will investigate the viability of several additional approaches:

- A four-dimensional preflight path planning algorithm that can re-route both horizontally and vertically, and control vehicle speeds.
- Implementation of one-way “corridors,” which funnel traffic in high-density regions into organized lines and groups of flights.

- Inflight rerouting, which identifies emerging conflicts and adjusts routes once a vehicle is already airborne.

7. References

Aljarboua, Z. (2009). Geometric Path Planning for General Robot Manipulators. *Proceedings of the World Congress on Engineering and Computer Science* .

Golding, R. (2018). *TR-004: Metrics to Characterize Dense Airspace Traffic.* Altiscope (A^3 by Airbus).

Sachs, P. (2018). *TR-002: Metrics for Near-Miss Events.* Altiscope (A^3 by Airbus).

Annex A: Loss of Separation Rates by Effective Flights per Hour

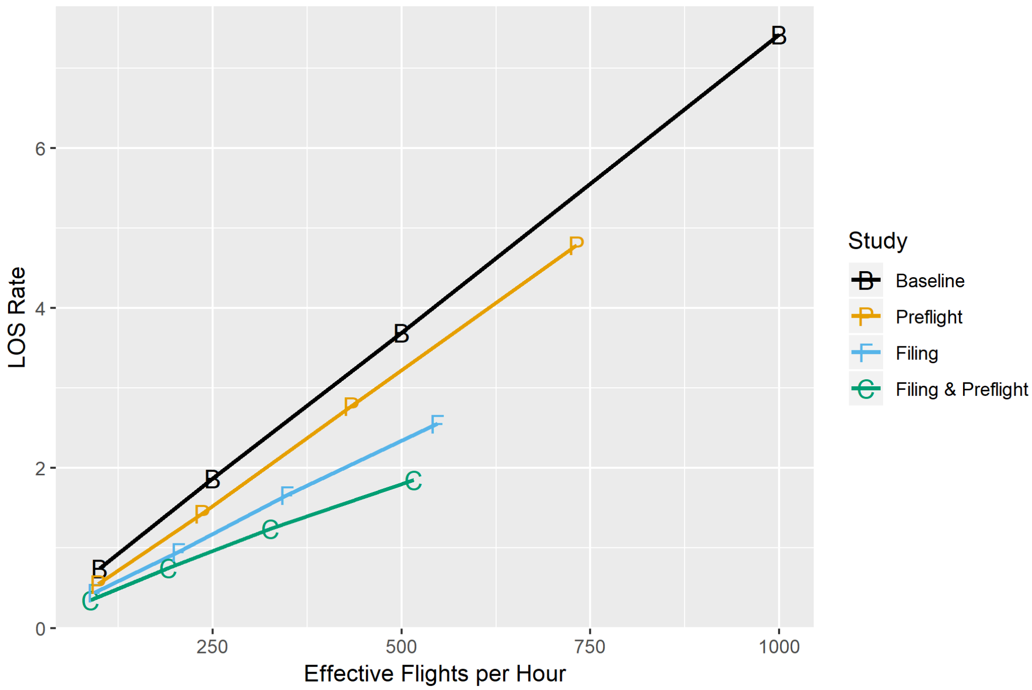

Figure 7: Uniform Region Loss of Separation Rates

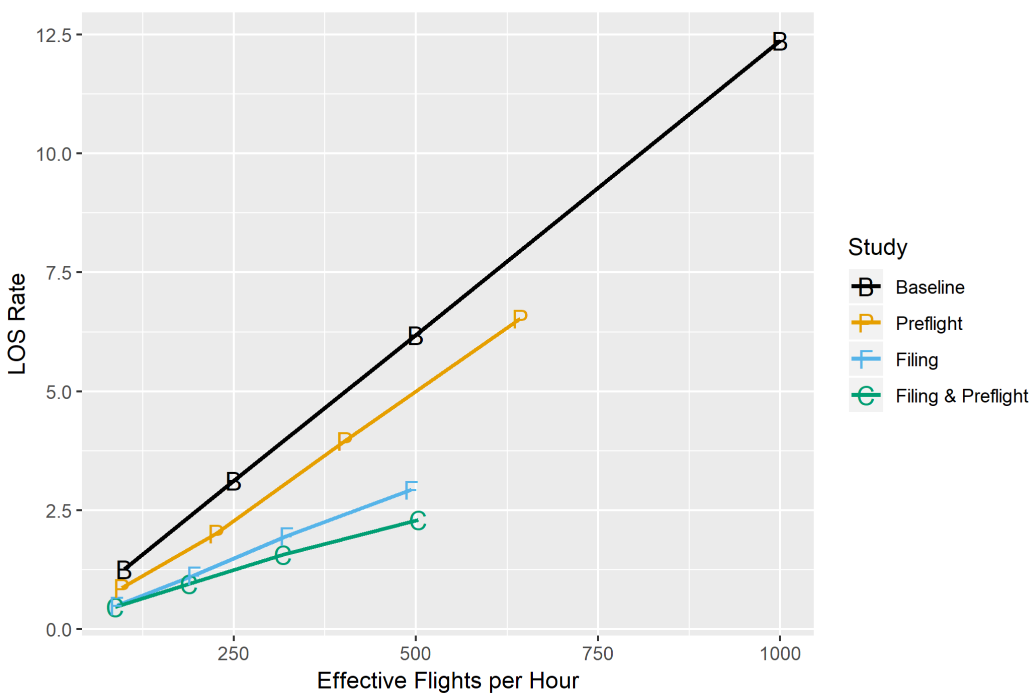

Figure 8: Gaussian Region Loss of Separation Rates

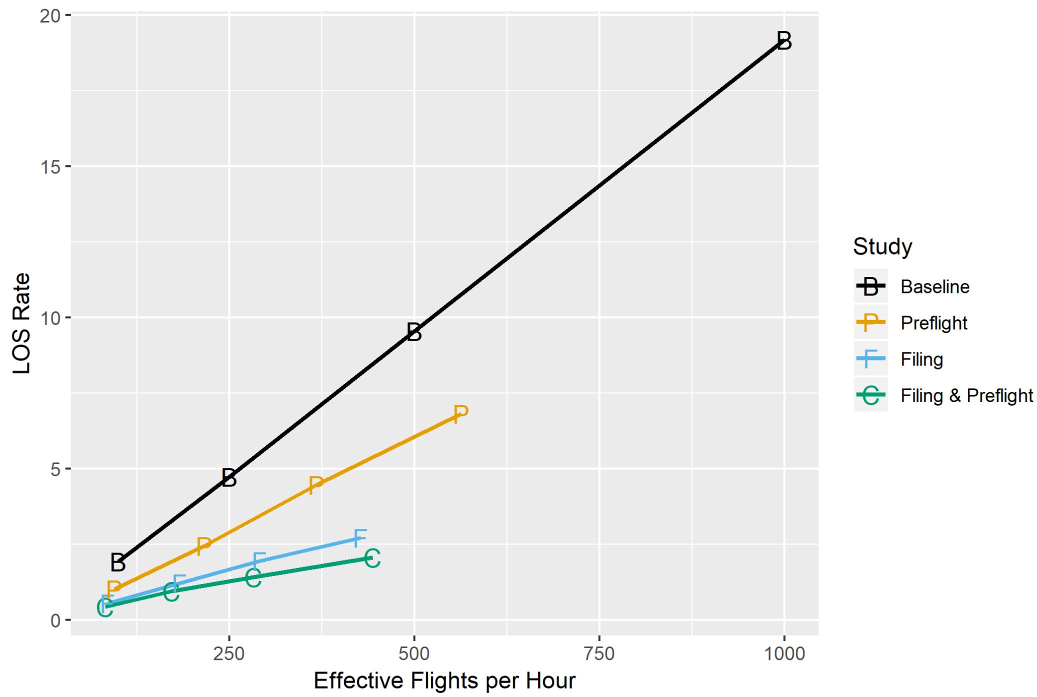

Figure 9: Bimodal Region Loss of Separation Rates

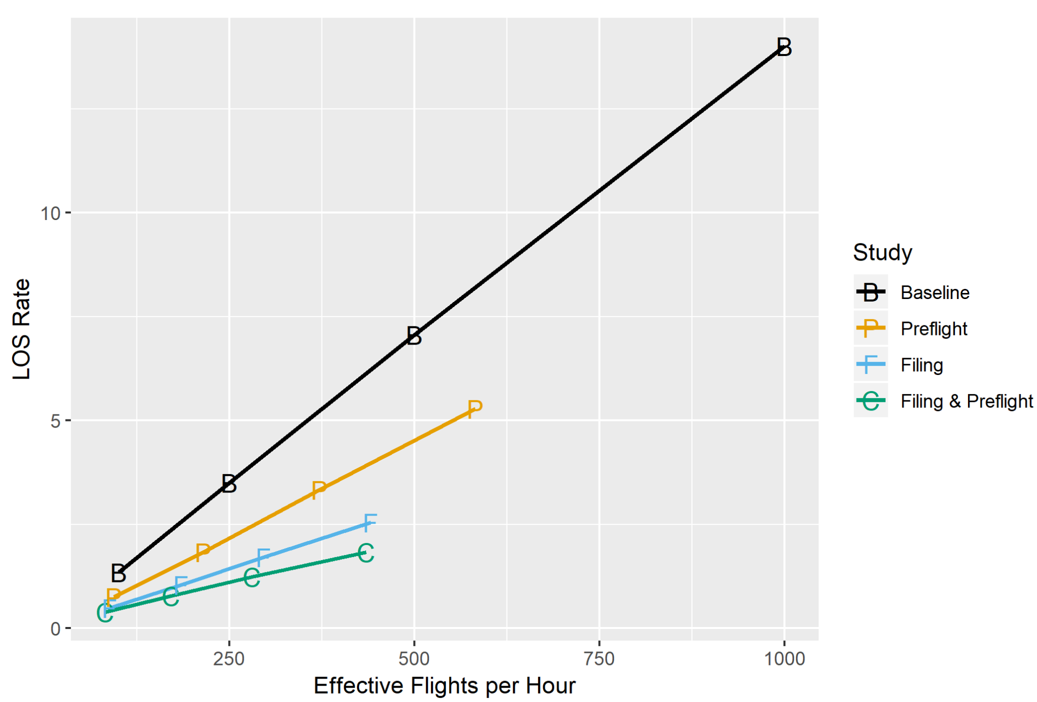

Figure 10: Shenzhen Region Loss of Separation Rates

Annex B: Pairwise Comparisons between Deconfliction Methods

Denote $\lambda_{r,v}^{method}$ to be the rate for a fixed region r, flight volume v, and deconfliction $method$. Using this notation, we can estimate the differences in deconfliction methods for the pairwise comparisons:

$$(\lambda_{r,v}^{none} - \lambda_{r,v}^{pre}),\ (\lambda_{r,v}^{pre} - \lambda_{r,v}^{filing}),\ (\lambda_{r,v}^{filing} - \lambda_{r,v}^{filing+pre}), (\lambda_{r,v}^{none} - \lambda_{r,v}^{filing+pre}).$$

In the following tables, the numerical values represent the 99-percent confidence interval ranges in the difference of losses of separation per flight hour for the given comparison. For example, the comparison at the top right of the first table below can be read as, "At 1,000 flights per hour in the Uniform region, there are 2.63 (the mean value) fewer losses of separation per flight hour with preflight deconfliction than with no deconfliction applied."

Ranges in red, which include a negative value, are not statistically significant. There were relatively few collisions across scenarios, so a number of comparisons are not statistically significant, or there were not enough observed events to construct a meaningful comparison.

	No Deconfliction vs Preflight Deconfliction $(\lambda_{r,v}^{none} - \lambda_{r,v}^{pre})$			
Loss of Separation: 99% CIs				
Region	**100 fph**	**250 fph**	**500 fph**	**1000 fph**
Uniform	(0.083, 0.305)	(0.327, 0.552)	(0.804, 1.030)	(2.517, 2.742)
Gaussian	(0.210, 0.577)	(0.931, 1.295)	(2.036, 2.402)	(5.656, 6.020)
Shenzhen	(0.441, 0.747)	(1.509, 1.821)	(3.566, 3.880)	(8.576, 8.889)
Bimodal	(0.718, 1.132)	(2.079, 2.492)	(4.880, 5.297)	(12.152, 12.568)
Airprox A+B: 99% CIs				
Uniform	(-0.013, 0.089)	(0.056, 0.160)	(0.142, 0.247)	(0.519, 0.623)
Gaussian	(0.020, 0.177)	(0.143, 0.297)	(0.34, 0.495)	(1.015, 1.172)
Shenzhen	(0.082, 0.213)	(0.289, 0.423)	(0.643, 0.777)	(1.621, 1.755)
Bimodal	(0.149, 0.330)	(0.405, 0.583)	(0.949, 1.131)	(2.391, 2.572)
Collision: 99% CIs				
Uniform	Small Sample	(-0.008, 0.012)	(-0.005, 0.017)	(0.015, 0.037)
Gaussian	Small Sample	(-0.017, 0.015)	(0.000, 0.032)	(0.025, 0.058)
Shenzhen	Small Sample	(-0.005, 0.021)	(0.013, 0.041)	(0.048, 0.076)
Bimodal	Small Sample	(-0.007, 0.032)	(0.011, 0.051)	(0.067, 0.106)

Table 3: Pairwise ratios of safety event rates with and without preflight deconfliction, by region and flights per hour.

	Preflight Deconfliction vs Filing Service $\left(\lambda_{r,v}^{pre} - \lambda_{r,v}^{filing}\right)$			
Loss of Separation: 99% CIs				
Region	**100 fph**	**250 fph**	**500 fph**	**1000 fph**
Uniform	(0.010, 0.208)	(0.378, 0.578)	(1.012, 1.215)	(2.134, 2.334)
Gaussian	(0.221, 0.519)	(0.734, 1.031)	(1.852, 2.155)	(3.449, 3.746)
Shenzhen	(0.149, 0.391)	(0.670, 0.917)	(1.499, 1.750)	(2.604, 2.855)
Bimodal	(0.302, 0.613)	(1.073, 1.390)	(2.357, 2.677)	(3.945, 4.261)
Airprox A+B: 99% CIs				
Uniform	(-0.029, 0.064)	(0.041, 0.133)	(0.189, 0.282)	(0.432, 0.524)
Gaussian	(-0.001, 0.123)	(0.078, 0.204)	(0.276, 0.405)	(0.593, 0.723)
Shenzhen	(0.002, 0.097)	(0.081, 0.184)	(0.248, 0.353)	(0.434, 0.540)
Bimodal	(0.013, 0.139)	(0.150, 0.282)	(0.405, 0.542)	(0.706, 0.840)
Collision: 99% CIs				
Uniform	Small Sample	Small Sample	(0.005, 0.024)	(0.012, 0.032)
Gaussian	Small Sample	(-0.010, 0.021)	(0.005, 0.031)	(0.017, 0.045)
Shenzhen	Small Sample	Small Sample	(0.000, 0.023)	(0.007, 0.030)
Bimodal	Small Sample	Small Sample	(0.012, 0.044)	(0.002, 0.053)

Table 4: Pairwise ratios of safety event rates between preflight deconfliction and the filing service, by region and flights per hour.

	Filing Service vs both Filing Service and Preflight Deconfliction $\left(\lambda_{r,v}^{filing} - \lambda_{r,v}^{filing+pre}\right)$.			
Loss of Separation: 99% CIs				
Region	**100 fph**	**250 fph**	**500 fph**	**1000 fph**
Uniform	(0.004, 0.186)	(0.113, 0.294)	(0.335, 0.516)	(0.614, 0.792)
Gaussian	(-0.096, 0.162)	(0.051, 0.309)	(0.259, 0.518)	(0.512, 0.763)
Shenzhen	(-0.006, 0.204)	(0.157, 0.369)	(0.365, 0.579)	(0.615, 0.829)
Bimodal	(-0.004, 0.256)	(0.136, 0.403)	(0.394, 0.658)	(0.518, 0.776)
Airprox A+B: 99% CIs				
Uniform	(-0.022, 0.065)	(0.025, 0.107)	(0.053, 0.137)	(0.120, 0.201)
Gaussian	(-0.035, 0.069)	(-0.019, 0.092)	(0.039, 0.149)	(0.095, 0.203)
Shenzhen	(-0.043, 0.042)	(0.022, 0.109)	(0.057, 0.144)	(0.119, 0.207)
Bimodal	(-0.027, 0.076)	(-0.020, 0.092)	(0.052, 0.162)	(0.096, 0.202)
Collision: 99% CIs				
Uniform	Small Sample	Small Sample	(-0.008, 0.010)	(-0.001, 0.016)
Gaussian	Small Sample	Small Sample	(-0.014, 0.009)	(-0.005, 0.019)
Shenzhen	Small Sample	Small Sample	(-0.003, 0.016)	(0.000, 0.021)
Bimodal	Small Sample	Small Sample	(-0.003, 0.022)	(-0.002, 0.024)

Table 5: Pairwise ratios of safety event rates between filing service alone, and scenarios with both preflight deconfliction and the filing service, by region and flights per hour.

	No Deconfliction vs both Filing Service and Preflight Deconf. $\left(\lambda_{r,v}^{none} - \lambda_{r,v}^{filing+pre}\right)$.			
Loss of Separation: 99% CIs				
Region	**100 fph**	**250 fph**	**500 fph**	**1000 fph**
Uniform	(0.294, 0.502)	(1.017, 1.225)	(2.352, 2.56)	(5.463, 5.669)
Gaussian	(0.629, 0.963)	(2.009, 2.342)	(4.445, 4.776)	(9.91, 10.237)
Shenzhen	(0.822, 1.104)	(2.578, 2.864)	(5.677, 5.962)	(12.042, 12.326)
Bimodal	(1.321, 1.697)	(3.598, 3.974)	(7.944, 8.319)	(16.924, 17.298)
Airprox A+B: 99% CIs				
Uniform	(0.029, 0.126)	(0.213, 0.308)	(0.477, 0.573)	(1.163, 1.257)
Gaussian	(0.104, 0.247)	(0.326, 0.468)	(0.782, 0.922)	(1.83, 1.971)
Shenzhen	(0.134, 0.258)	(0.493, 0.614)	(1.051, 1.171)	(2.277, 2.399)
Bimodal	(0.257, 0.424)	(0.664, 0.828)	(1.539, 1.702)	(3.323, 3.484)
Collision: 99% CIs				
Uniform	Small Sample	Small Sample	(0.011, 0.032)	(0.045, 0.066)
Gaussian	Small Sample	Small Sample	(0.017, 0.047)	(0.065, 0.095)
Shenzhen	Small Sample	Small Sample	(0.033, 0.058)	(0.079, 0.104)
Bimodal	Small Sample	Small Sample	(0.052, 0.086)	(0.117, 0.151)

Table 6: Pairwise ratios of safety event rates between scenarios without deconfliction, and scenarios with both preflight deconfliction and the filing service, by region and flights per hour.