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Airspace Saturation and Midair Collision Risk: A Case Study at a Class D Airport

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Midair collisions (MACs) continue to occur between aircraft despite the presence of aircraft collision avoidance systems (ACAS) and air traffic control (ATC) services. While MACs involving transport category aircraft and airlines are now extremely rare events, with the last incident occurring in 2015, MACs continue to occur involving general aviation aircraft (BEA Senegal, 2018). Between January 2000 and June 2010, a total of 112 MACs in the United States were investigated by the National Transportation Safety Board (NTSB) (Kunzi & Hansman, 2013). All these accidents involved at least one aircraft operating under Visual Flight Rules (VFR), which involves the use of visual aids as the primary means of navigation and flight by the pilot/s. Fifty-nine percent (59%) of these incidents occurred at or in the vicinity of an airport. A further 93 collisions were reported and investigated between July 2010 and December 2021 (NTSB, 2022). Eighty-eight of the 93 incidents involved a general aviation (GA) aircraft. Of all the MACs in the United States since January 2000, none involved a scheduled air carrier (Part 121) operation.

In addition to MACs, near midair collisions (NMACs) are commonly reported through the Federal Aviation Administration's (FAA) Near Midair Collision System (NMACS) and the National Aeronautics and Space Administration (NASA) Aviation Safety Reporting System (ASRS) (FAA Aviation Safety Information Analysis and Sharing (ASIAS), n.d.-a; NASA, n.d.). A NMAC is defined as "an incident associated with the operation of an aircraft in which a possibility of collision occurs as a result of a proximity of less than 500 feet to another aircraft, or a report is received from a pilot or a flight crew member stating that a collision hazard existed between two or more aircraft" (FAA, 2018, p. 997). The NMACS contains reports made to the FAA which are subsequently investigated by FAA inspectors, together with air traffic controllers. The data collected by the system informs and guides FAA programs, policies, and procedures with the aim of improving overall aviation safety and reducing NMACs through the lessons from reported incidents (FAA Aviation Safety Information Analysis and Sharing (ASIAS), n.d.-b). The NASA ASRS similarly collects reports made to the system which are reviewed and anonymized. Filing reports to either system includes a conditional waiver of sanction to promote reporting of such incidents. These reports, however, are subjective in their nature and are prone to underreporting and other biases as a result. Despite this, reports of NMACs are the most readily available when studying such events.

While no conclusive statistical relationship has been drawn between MACs and NMACs in literature likely due to the infrequency of MACs, an NMAC can be viewed as precursor events to a MAC as a condition that qualifies as an NMAC must occur prior to any MAC (Brooker, 2005). NMACs that do not result in MACs can either be a result of chance (aircraft flight paths were close but did not cross exactly) or avoided due to evasive maneuvers by one or both flight crews.

Identifying and studying NMACs can be beneficial in preventing MACs. Given that MACs are special cases of NMACs, reviewing NMACs can reveal underlying factors that contribute to the near misses, which may also lead to MACs. Through the identification of such factors, mitigating and control measures can be implemented to reduce the risk of such events from occurring.

Airspace saturation is one factor that has been commonly studied in relation to the number of NMACs (Alexander, 1970; Datta & Oliver, 1991; Datta & Oliver, 1992; Gifford & Sinha, 1991). Previous studies have found positive relationships between airspace saturation and NMACs whether through the comparison of reports with terminal airspace traffic or through the use of simulations. However, previous studies have relied on the use of theoretical assumptions about aircraft movements or solely on reported NMACs, which are unlikely to be representative of all NMACs and have accompanying reporting biases. Further, no relationship between reported NMACs and actual NMACs has been established as this type of study has been difficult to conduct till recently.

With the introduction and adoption of Automatic Dependent Surveillance-Broadcast (ADS-B), aircraft position information is easy to collect, and can be used to identify NMACs and other proximity events between aircraft. ADS-B is an aircraft surveillance technology introduced as part of the FAA’s Next Generation Air Transportation System (NextGen) project. Aircraft identification and position information is transmitted by transponders, eliminating the need for primary or secondary surveillance radar to identify and locate aircraft. Since 2020, ADS-B is required in most types of U.S. airspaces, and approximately 70% of US-registered aircraft are ADS-B equipped (Bureau of Transportation Statistics, 2020; Federal Aviation Administration, n.d.).

For this case study, the area surrounding the Purdue University airport (KLAF) was used. KLAF is a class D airport (has an air traffic control tower (ATCT)) and is the second busiest airport in Indiana despite having no scheduled commercial service. Most operations at the airport involve general aviation operations and flight training. As such, most of the operations are conducted under Visual Flight Rules (VFR). Further, areas surrounding the airport are used as practice areas for training maneuvers. Flight operations by the university utilize “practice areas” while flight operations by the local FBO do not.

NMACs are regularly reported to the university’s internal safety reporting system. From June to November 2021, a total of 13 NMAC reports were filed. In addition, one report was filed to the NASA ASRS of a NMAC occurring at the airport during the same period. A comparison of reports made to the university’s internal system, the NASA ASRS, FAA NMACS, and NMACs identified using ADS-B data is detailed in another article.

The busy airspace surrounding the airport has caused local concern for the further expansion of training operations at the airport due to the expected increase in potential for NMACs in increasingly congested airspace. Hence, identifying the relationship between airspace saturation and NMACs or proximity events can guide decision makers in deciding to expand operations, and in pursuing strategies to mitigate collisions risks.

The research questions the study answers are what is the relationship between airspace saturation and proximity events, and how does class D airspace (air traffic control tower covering the ground and immediate vicinity of an airport) affect this relationship? In practice, the answers to these questions may suggest how training aircraft should be distributed in the airspace surrounding KLAF.

Methodology

To determine the relationship between airspace congestion and proximity events, ADS-B data from the area surrounding KLAF were collected over 180 days from June 4, 2021, to November 30, 2021. The ADS-B data were then filtered to only include aircraft positions reported within an approximate 50 by 50 statute mile area surrounding the airport and at altitudes up to 8,000 feet (pressure altitude). The data were further filtered using an unscented Kalman filter (UKF) and interpolation algorithm to smooth and interpolate position data such that aircraft position information was available for every second. The volume studied includes the towered (Class D) airspace surrounding KLAF, and the training areas commonly used by the University and local FBO.

The total volume was further divided into 25 smaller volumes, forming grids in the latitudinal and longitudinal dimensions. Each grid square was 0.145 degrees in latitude and 0.190 degrees in longitude, which is approximately 10 by 10 statute miles. As boundaries were determined using the approximate degrees of longitude equivalent to 10 statute miles at the latitude of the airport's position, grid squares were increasingly larger from south to north. A geodesic equation provided by Karney (2013), and the Pythagorean theorem were used to calculate the distance between aircraft. The distance between reported aircraft positions was calculated using Karney's equation. While the equation assumes the coordinates provided to be on the surface of the earth, the resulting errors were assumed to be insignificant at the low altitudes being studied. The Pythagorean theorem was then applied to both the lateral distance and the difference in reported altitude for the ADS-B positions being compared to calculate the "slant" (direct) distance between aircraft.

Aircraft positions reported to be within 1,000 feet of each other at a given second were then tabulated then manually reviewed to verify that an actual proximity event occurred. The review was conducted by a certificated commercial pilot with flight experience at KLAF. Proximity events due to formation flights, helicopters on the ramp, aircraft on taxiways, or inconsistent data were removed. 1,000-foot rather than 500-foot (quantitative NMAC definition) proximity events were studied as all qualitative NMACs submitted to the university's safety reporting system involved actual proximity distances of greater than 500 feet.

Conversely, the authors determined that events involving distances greater than 1,000 feet are more likely insignificant.

To determine airspace saturation at a given time, the number of unique callsigns present in each grid square over a 15-minute period was counted. This was done for every grid square for every 15-minute period from the beginning to the end of the study period. Each proximity event was then tied to the corresponding grid square saturation during the 15-minute period that it occurred. This resulted in counts of proximity events at different airspace densities. The number of proximity events at a given saturation was then normalized by dividing the count over the total number of periods when such airspace saturation occurred.

Given the data, a logistic regression analysis was performed to determine the relationship between the probability of an occurrence of a proximity event (Y) with airspace saturation (X1) and airspace type (X2) (controlled or not). It was expected that as saturation increases, the proportion of periods with a proximity event would also increase. As no underlying normal distribution is expected for the occurrence of a proximity event, a logit link was used (see Equation 1).

$$\ln\left(\frac{Y}{1-Y}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \tag{1}$$

When building the model, data from airspace saturation values below 0.02 aircraft per square mile (equivalent to fewer than two aircraft in each studied grid period) were excluded, since such data eliminates the possibility of a collision.

Independence between grid-periods was assumed, although some sort of relationship is probable due to the time-series nature of the data, and the adjacency of grids. The linearity of log odds of the dependent variable with the independent variables were also checked, together with the presence of highly influential outliers, and multicollinearity.

Results

A total of 187, 1,000-foot (or less) proximity events were identified during the period studied. This includes 17 incidents that would qualify as an NMAC (less than 500 feet of separation between aircraft). Ten proximity events occurred within the same grid-periods. Thus, 177 of the 420,000 grid-periods covered had proximity events. Grid-periods with airspace densities less than 0.02 aircraft per square mile (equivalent to less than two aircraft in the grid-period) were excluded from the model building process (as no proximity event would be possible).

The distribution of the number of grid-periods with a specific airspace saturation level with and without proximity events can be seen in Tables 1 and 2. From the data, it can be seen that a maximum airspace saturation level of 0.17 aircraft per square mile was reached in the area covering the airport's Class D airspace (see Table 1), while only a maximum of 0.10 aircraft per square mile was reached in the areas excluding that surrounding the Class D airspace (see Table 2).

Table 1
Observed Data within the Class D Airspace

Aircraft per square mile	Periods with Proximity Events	Total Grid-Periods	Event Probability
0	0	7232	0
0.01	0	2178	0
0.02	2	1330	0.0015
0.03	7	1062	0.0066
0.04	8	907	0.0088
0.05	7	832	0.0084
0.06	14	784	0.0179
0.07	7	641	0.0109
0.08	11	581	0.0189
0.09	13	451	0.0288
0.10	9	334	0.0269
0.11	4	199	0.0201
0.12	11	143	0.0769
0.13	1	63	0.0159
0.14	3	39	0.0769
0.15	0	7	0
0.16	0	11	0
0.17	0	5	0
0.18	0	1	0

Table 2

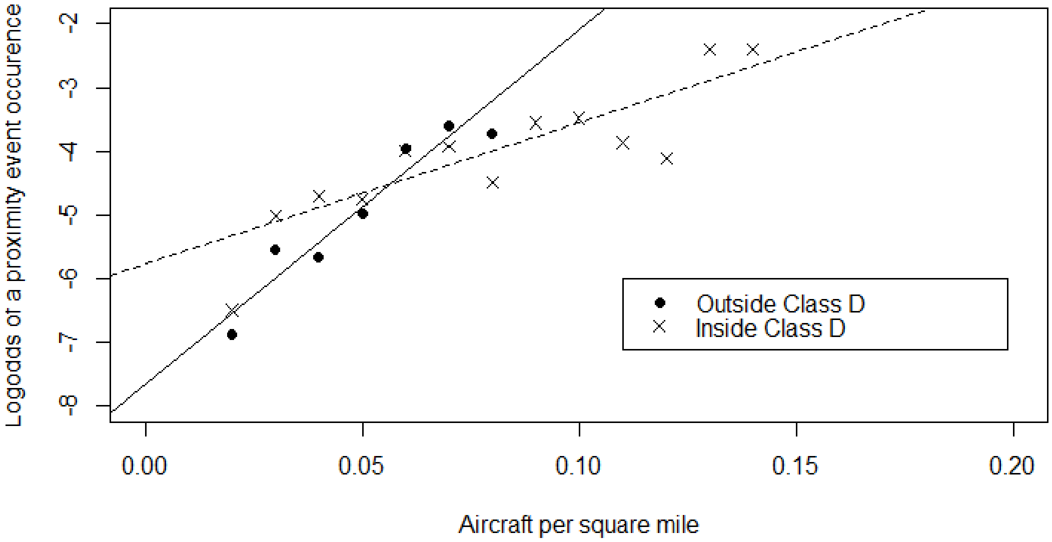
Observed Data Outside the Class D Airspace

Aircraft per square mile	Periods with Proximity Events	Total Grid-Periods	Event Probability
0	0	312636	0
0.01	0	58003	0
0.02	21	20264	0.0010
0.03	30	7781	0.0039
0.04	10	2921	0.0034
0.05	7	1029	0.0068
0.06	7	370	0.0189
0.07	3	131	0.0229
0.08	1	39	0.0256
0.09	0	13	0
0.10	0	3	0
0.11	0	0	N/A
0.12	0	0	N/A
0.13	0	0	N/A
0.14	0	0	N/A
0.15	0	0	N/A
0.16	0	0	N/A
0.17	0	0	N/A
0.18	0	0	N/A

A linear relationship was found between the log odds of a proximity event and air-space saturation, confirming the appropriate use of logistic regression (Figure 1). This relationship was further confirmed as the coefficient of the log of the airspace saturation was insignificant when added as an interaction term. A different relationship/slope can clearly be seen between the log odds of a proximity event occurring within as compared to outside the Class D airspace.

Figure 1

Log Odds of a Proximity Event Versus Aircraft per Square Mile



Based on the results of the logistic regression analysis, the log odds of a proximity event increase by 0.5575 for every 0.01 increase in airspace saturation. However, this relationship is affected by whether the area is part of the Class D or not. Within the Class D, the baseline probability of a proximity event is higher than outside the Class D with a log odds ratio of 1.9080 more than outside the Class D, but the log odds increase at a reduced rate – increasing by a ratio of 0.2208 instead. All log odds calculated through the regression were significant at the 99% significance level.

Table 3

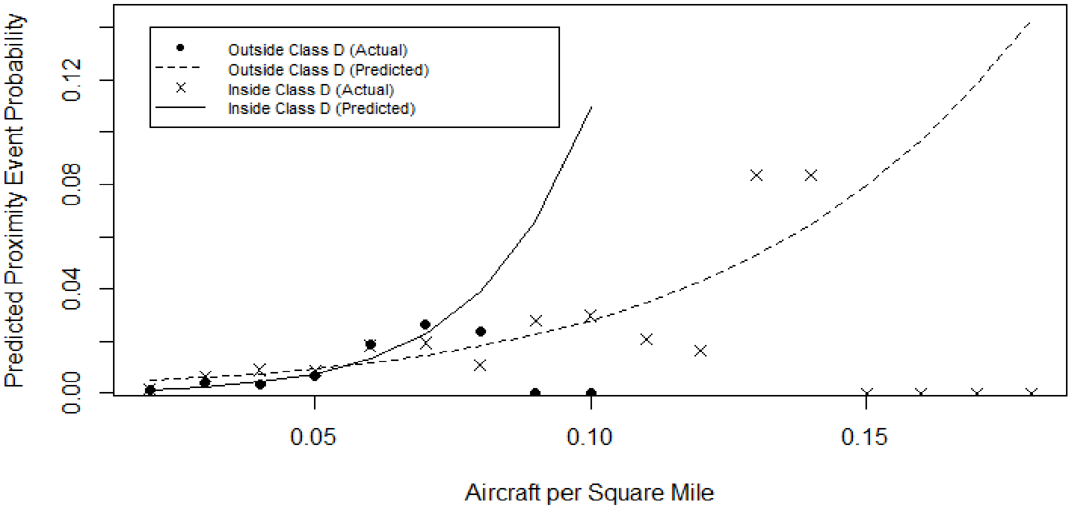
Logistic Regression Results

Variables	Odds Ratio
Constant	-7.6708*** (0.2609)
Airspace Saturation	55.7501*** (6.7145)
Class D	1.9080*** (0.3631)
Airspace Saturation: Class D	-33.6743*** (7.3555)
Null Deviance	2260.8
Residual Deviance	2043.1
Pseudo R Squared	
McFadden	0.0963
Cox and Snell	0.0054
Nagelkerke	0.0988
Number of Observations	39,951

Based on the output of the regression model, the relationship between 1,000-foot proximity events and airspace saturation is described. At the saturation levels covered by the studied data, an increase in airspace saturation leads to an exponential increase in the probability of a proximity event. A comparison of the logistic model compared to observed data can be seen in Figure 2.

Figure 2

Logistic Model Compared to Observed Data



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Multicollinearity was found to be a potential issue based on a calculated point-biserial coefficient 95% confidence interval of (0.588, 0.600). Airspace saturation was found to be strongly correlated with the airspace being controlled (Class D). This was expected as most flights in the area originate and terminate at the airport, which is controlled, and naturally sees the highest saturation of operations – hence the need for a control tower. While the inclusion of both these variables in the regression model inflates the variance of the estimators, the impact and significance of the including the class D airspace as a predictor is obvious when looking at the plot of log odds and saturation. As such, the Class D variable was kept as an integral part of the model.

Discussion

The results of the logistic regression show that the probability of a proximity event rapidly increases as airspace saturation increases. Further, it shows that the probability of a proximity event increases at a greater rate in uncontrolled airspace than it does within the controlled, Class D, airspace. However, the probability of a proximity event within the Class D airspace is higher at the lowest airspace saturation levels. A possible explanation for these phenomena is that the Class D airspace is a more complex environment that requires aircraft to converge and operate in greater proximity when entering/exiting the traffic pattern for departure or arrival, leading to a greater probability of a proximity event. On the other hand, the presence of an ATCT mitigates the effect of increased traffic and airspace saturation by providing clearances, instructions, and traffic alerts to all aircraft within its airspace.

The findings of this work provide information that may help operators and other stakeholders at KLAF. By knowing the relationship between proximity events and airspace saturation, aircraft can be dispatched to minimize the potential for conflicts and NMACs. Decision makers are also given the information to target maximum air-space densities for operations. While caution must be exercised in extrapolating these findings, regulators and other operators may also use this information to guide their decisions as well. More importantly, this provides a proof-of-concept for the use of ADS-B information in studying airspace interactions and saturation which can be performed at a larger scale or in other environments to study.

Limitations of this work include the use of 1,000-foot proximity events as the basis for determining a significant event. While the authors determined this to be a reasonable threshold, aircraft may safely cross paths at distances less than 1,000 feet apart. For example, some identified proximity events involved an aircraft on short final for one runway while another aircraft was on downwind for an intersecting runway, usually around 500 feet or more above the aircraft on final. These events occurred within the Class D airspace and most probably involved ATC instructions. As these scenarios were repeated a few times, it appears to be accepted practice. Additionally, no differentiation was made between vertical and lateral distances. While a distance of 500 feet laterally could lead to a collision within one and a half seconds in a head-on scenario (assuming a ground speed of 100 knots), a 500-foot vertical separation may have extremely low collision potential when aircraft are maintaining a fixed altitude. The formal definition of an NMAC being a proximity event of 500 feet or less may be too simplistic. Future studies can take the differing risks of vertical and lateral separation distances into account.

Another limitation with the work performed is the uncertainty of the accuracy of the ADS-B data. While regulatory requirements on the accuracy and latency of trans-mitted data exist, the actual accuracy of individual ADS-B receivers is unknown (“Automatic Dependent Surveillance-Broadcast (ADS-B) Out equipment performance requirements,” 2010). Previously found in a comparison of ADS-B data versus onboard avionics equipment were means of 58 feet and 112 feet for lateral and vertical errors, respectively (Dy & Mott, 2022). Albeit, in the study performed, errors inherent with the comparison method used were expected in that range. Additionally, the UKF and interpolation method used in this study, described previously in (Dy et al., 2021), has additional errors over the raw ADS-B data. These have been found to exceed 1,000 feet in at least one case. While gross issues with relation to this filtering and interpolation method should have been caught and eliminated during the manual review of identified conflict events, it is possible that some calculated distances are inaccurate due to this.

Conclusion

Based on a logistic regression analysis, a conclusive relationship between airspace saturation and the occurrence of midair proximity events was found in the airspace surrounding the Purdue University airport. In the six-month study performed, it was found that the probability of a proximity event occurring in the Class D controlled airspace immediately around the airport was greater to begin with but increased at a lesser rate than that outside the airspace. The findings of this study can provide guidance for operators and stakeholders at the Purdue University airport in planning their operations and use of the available airspace. It also serves as a proof-of-concept for using ADS-B data to study NMAC risk, which can be reproduced at a larger scale or at other airports and airspaces.

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