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A Comparison of Airport Risks: Unmanned Aircraft Systems (UAS) Sightings, Wildlife Strikes, and Runway Incursions

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Abstract

To provide a context for the potential threat of unmanned aircraft systems (UAS) sightings on airport operations, this paper compares the characteristics of UAS sightings with two common airport threats: wildlife strikes and runway incursions. This study analyzed over 60,000 events in a three-year period (September 2016 to August 2019), including 6,551 UAS sightings from the Federal Aviation Administration (FAA) UAS Sightings Report database, 47,574 wildlife strikes from the FAA Wildlife Strike database, and 6,041 runway incursions from the FAA Runway Safety database. The results suggest both similarities and differences among the airport threats. Both UAS sightings and wildlife strikes vary by time of year and time of day. UAS sightings and wildlife strikes farther from the airport occur at higher altitudes than sightings and strikes occurring close to the airport. However, UAS sightings are reported at higher altitudes than wildlife strikes, and the distance of UAS sightings from the airport is farther than that of wildlife strikes, in general. The severities of UAS sightings and runway incursions are similar. Pilots take evasive actions in three percent of UAS sightings, and runway incursions of severity A and B are also rare. Pilots of general aviation (GA) aircraft reported the most UAS sightings, and GA operations are also involved in more runway incursions. Considering the kind of airport affected, UAS sightings and wildlife strikes are more common at primary airports, notably large and medium hub airports, whereas runway incursions are more common at reliever airports. Generally, UAS have had a minimal impact on airport operations despite their growing prevalence, which reflects the overall success of integrating this new airspace user into the national airspace system.

Keywords: unmanned aircraft systems, UAS, UAS sighting, wildlife strike, runway incursion, drone, airport safety

Introduction

Safety is the top priority for the aviation industry and a safe airport environment is essential to aviation safety. Due to the increasing prevalence of unmanned aircraft systems (UAS) in recent years, UAS sightings have become a potential threat to airport operations. To address the threat of UAS sightings, the Federal Aviation Administration (FAA, 2020a) has been collecting and publishing UAS sighting reports since 2014. Since UAS sightings are a relatively new threat to airport

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operations, it is helpful to compare the characteristics of UAS sightings with other well-known airport threats: wildlife strikes and runway incursions.

This study analyzed over 60,000 UAS sightings (including small UAS weighing less than 55 lbs and UAS weighing 55 lbs or more), wildlife strikes, and runway incursions in a three-year period from September 2016 through August 2019. These events include 6,551 UAS sightings from the FAA UAS Sightings Report database, 47,574 wildlife strikes from the FAA Wildlife Strike database, and 6,041 runway incursions from the FAA Runway Safety (RWS) database. Characteristics of UAS sightings are compared with characteristics of wildlife strikes and runway incursions. Airport rankings for each risk are tabulated, with consideration of the airport category.

Background

UAS can damage aircraft (D'Souza et al., 2017), present a threat to aircraft in flight, and disrupt airport operations, causing delay and shutdown. UAS sightings have been documented at airports around the world and, in some cases, UAS sightings at airports have drawn widespread public attention due to the disruption to airport activity and the threat to aviation safety. Table 1 shows examples of UAS sightings at commercial airports worldwide that have been reported in the media.

As shown in Table 1, the sighting of a drone (the aircraft component of a UAS) near an airport can disrupt airport operations, and result in delayed, diverted, or canceled flights, and airport closure. For example, on the evening of January 22, 2019, airline pilots reported a UAS in their approach path to Newark Liberty International Airport (EWR), which led the FAA to stop air traffic for 21 minutes (Shepardson, 2019; Silk, 2019). The agency received two reports of UAS operating near the airport from two airline pilots at 4:44 p.m. (Aratani, 2019; Cohen, 2019). One of the pilots said he saw what he believed to be a UAS at about 3,500 feet above Teterboro Airport. An air traffic controller who watched over airspace around EWR also spotted two UAS flying close to a plane ("FAA Investigating Drone Scare," 2019). Based on the reports, inbound flights to EWR were held in the air and takeoffs were momentarily stopped as a precaution (Dow, 2019). In total, 43 inbound flights were held in the air, ten were diverted to land at other airports, and another 170 flights bound for EWR were briefly delayed on the ground before taking off from other airports. The EWR stoppage marked the first and only shutdown at a major U.S. airport due to unauthorized UAS activities.

Given the risks to aircraft safety, airport operations, and aviation economics, it is valuable to understand the characteristics of UAS sightings. A better understanding of risks of UAS sightings at airports will help identify appropriate mitigation measures. Although new technologies and policies such as the requirement for UAS remote identification may provide one tool to increase safety, there is still a need to assess the potential threat of UAS based on actual UAS sightings. To understand the potential threat of UAS sightings to airport operations and to compare the threat with wildlife strikes and runway incursions, researchers reviewed studies in these three areas. The following three sections discuss research related to UAS sightings, wildlife strikes, and runway incursions, and introduce the FAA's UAS sighting database, wildlife strike database, and RWS database.

UAS Sightings Database and Research

The FAA has been collecting and publishing UAS sightings since 2014. As of July 1, 2020, the FAA (2020a) had released 9,968 reports for UAS sightings between November 2014 and March 2020. These UAS sightings were reported by commercial and general aviation (GA) pilots, concerned citizens, airport officers, law enforcement officers, passengers, military personnel, and air traffic controllers. UAS sightings are reported through the Flight Service District Office, a FAA field office responsible for numerous aircraft, air carrier and pilot issues, as well as accident reporting.

UAS sightings have not been widely studied in the USA. Previous studies on UAS sightings include the characteristics of 921 incidents involving UAS and manned aircraft research by Gettinger and Michel (2015), reports on UAS sightings by the Academy of Model Aeronautics (AMA, 2016, 2017), analysis of 3,417 UAS sighting reports by the Unmanned Aircraft Safety Team (UAST, 2017), and an investigation of 6,551 UAS sighting reports and how they relate to airports by Wang and Hubbard (2021). Table 2 shows the most important findings from these studies.

The findings of previous studies suggest generally consistent characteristics of UAS sightings; however, previous research has focused on characteristics of UAS sightings. This paper expands the discussion to include comparisons between UAS sightings and wildlife strikes or runway incursions, which are well-known airport risks.

Wildlife Strikes Database and Research

The FAA has supported airport wildlife management and related research for many years. FAA (2020b) addresses wildlife strikes through a number of initiatives, including regulatory guidance for wildlife hazard assessment and wildlife hazard management plans, the collection and publication of wildlife strike reports through the FAA's Wildlife Strike Database, outreach to the GA community to encourage wildlife strike reporting, conducting research and development projects to aid airports with the mitigation

Table 1
UAS Sightings at large airports, September 2018–August 2020.

Event date	Airport	Location	Impacts of UAS sighting on airport and flights	Airport annual enplanements
November 11, 2018	Wellington Airport	Wellington, New Zealand	The airspace around the airport was closed for 30 minutes (Gudsell, 2018)	6.1 million in 2018 (Wellington Airport, 2019)
December 19–21, 2018	Gatwick Airport	Horley, UK	The airport was closed for 33 hours; about 1,000 flights were diverted or canceled; around 140,000 passengers were affected (Yeginsu, 2018)	36.8 million in 2019 (Ivy Holdco Limited, 2020)
January 8, 2019	Heathrow Airport	Longford, UK	The departing runway was closed for an hour (Martin, 2019)	81 million in 2019 (Heathrow Airport Limited, 2020)
January 22, 2019	Newark Liberty International Airport	Newark, New Jersey	Inbound traffic was halted for 21 minutes; 43 flights were held in the air; nine flights were diverted (Shepardson, 2019)	46.3 million in 2019 (The Port Authority of NY & NJ, 2020)
February 15, 2019	Dubai International Airport	Dubai, UAE	Flight departures were suspended for 30 minutes (Wolgelenter, 2019)	86.4 million in 2019 (Dubai Airports, 2019)
March 22, 2019	Frankfurt Airport	Frankfurt, Germany	Air traffic was halted for 30 minutes (GardaWorld, 2019)	70.6 million in 2019 (Fraport, 2020)
April 28, 2019	Gatwick Airport	Horley, UK	Three flights were diverted (Forrest, 2019)	36.9 million in 2019 (Ivy Holdco Limited, 2020)
May 9, 2019	Frankfurt Airport	Frankfurt, Germany	The airport was closed for an hour; more than 100 flights were canceled (Lomas, 2019)	70.6 million in 2019 (Fraport, 2020)
June 18, 2019	Singapore Changi Airport	Singapore	A runway was shut down for 10 hours; 37 flights were delayed; one flight was diverted (Yu, 2019)	68.3 million in 2019 (Changi Airport Group, 2020)
July 12, 2019	Leeds Bradford Airport	Leeds, UK	The airport was closed for 45 minutes; flights were diverted to another airport (British Broadcasting Corporation, 2019)	3.7 million in 2019 (Burley & Menston Airport discussion, 2020)
September 22, 2019	Dubai International Airport	Dubai, UAE	Arrivals were disrupted for about 15 minutes; two flights were diverted (Reuters, 2019)	86.4 million in 2019 (Dubai Airports, 2019)
November 28, 2019	Sharjah International Airport	Sharjah, UAE	The airspace around the airport was closed; eight flights were diverted (Shurafa, 2019)	13.6 million in 2019 (Sharjah Airport, n.d.)
December 24, 2019	Muscat International Airport	Muscat, Oman	The airport was closed for 90 minutes; a number of flights were delayed or diverted (GulfInsider, 2019)	12.9 million in 2018 (Muscat International Airport, 2019)
February 2, 2020	Madrid Barajas International Airport	Madrid, Spain	The airport was closed for over an hour; 26 flights were diverted (ABC News, 2020)	61.7 million in 2019 (Aena, 2020)
March 2, 2020	Frankfurt Airport	Frankfurt, Germany	The airport was closed for two hours; multiple flights were delayed, diverted, or canceled (Hollan, 2020)	70.6 million in 2019 (Fraport, 2020)

Table 2
Findings of previous studies about UAS sightings.

Study	Number of UAS sightings analyzed (time)	Findings of UAS sightings
Gettinger and Michel (2015)	921 (Dec. 17, 2013 to Sep. 12, 2015)	• UAS sightings are most likely to occur during daytime. • Over half involving manned aircraft are GA aircraft. • UAS sightings beyond five miles of an airport occur at much higher altitudes than UAS sightings within five miles of an airport in general. • About 60 percent of UAS sightings occur within five miles from the reported airport. • Over 90 percent of UAS sightings occur above the FAA's 400-foot ceiling for UAS. • One-fourth of reports indicate the UAS-to-aircraft proximity is less than 500 feet. • Pilots take evasive action to avoid UAS in three percent of cases. • The top four cities for UAS sightings are New York, Los Angeles, Miami, and Chicago.
AMA (2016, 2017)	582 (Aug. 21, 2015 to Jan. 31, 2016); and 1,270 (Feb. 1, 2016 to Sep. 30, 2016)	• The top three months for UAS sighting reports are June, July, and August. • Ninety-three percent of UAS occur above the FAA's 400-foot ceiling for UAS. • About three percent of cases are reported as near miss. • Nearly 30 percent of reports are not referred to law enforcement department or law enforcement notification is unknown.
UAST (2017)	3,417 (Aug. 2015 to Mar. 2017)	• Over 70 percent of UAS sightings occur above the FAA's 400-foot ceiling for UAS. • Sixteen percent of reports indicate the UAS-to-aircraft proximity is less than 500 feet. • Pilots take evasive action to avoid UAS in 3.3 percent of cases.
Wang and Hubbard (2021)	6,551 (Sep. 1, 2016 to Aug. 31, 2019)	• The top three months for UAS sighting reports are June, July, and May. • Three-fourths of UAS sightings occur between 11 a.m. and 6 p.m. local time. • Over 90 percent of UAS sightings are reported by pilots. • Pilots of GA aircraft and business jets report the most UAS sightings. • Pilots are more likely to report UAS that are below or close to their aircraft. • Over 90 percent of UAS sightings occur above the FAA's 400-foot ceiling for UAS. • About 60 percent of UAS sightings occur within five miles from the reported airport. • Pilots take evasive action in only 3.3 percent of cases. • Law enforcement is notified or follow-up actions are taken by relevant departments in three-fourths of UAS sightings. • States that have large populations and cities with higher population densities have more UAS sightings. • UAS sightings are more likely to be reported close to large and medium hub airports.

of wildlife hazards, and partnerships with domestic and international aviation organizations.

The FAA's Wildlife Strike Database provides a database for research and provides information to support wildlife management programs that mitigate risk. The FAA first attempted to collect wildlife strike data in the 1960s (Dolbeer, 2011); since 1990, the FAA (2020c) and the U.S. Department of Agriculture (USDA) have collected data on wildlife strikes to better understand the scope and nature of the issue. In April 2009, the FAA (2020b) made its entire database available to the public. The Wildlife Strike Database contains wildlife strikes voluntarily reported by airlines, airports, pilots, and other sources. A wildlife strike report includes fields for incident date and time, airport information, operator and aircraft, environment conditions, damage and cost, impact and damage, wildlife information, and reporter contact information. It is also possible to upload images of the wildlife strike to the database (FAA, 2020d).

The number of wildlife strikes reported per year to the FAA has increased 8.3-fold from about 2,102 in 1990 to 17,367 in 2019. The number of U.S. airports with wildlife strikes increased from 335 in 1990 to a record of 753 in 2019. These numbers demonstrate increasing awareness and use of the reporting program.

Numerous studies have been conducted on wildlife strike management. Government agencies and researchers have used the FAA Wildlife Strike Database as a research tool to analyze the characteristics of wildlife strikes and improve aviation safety. For example, the FAA and USDA jointly published series reports on wildlife strikes to civil aircraft in the USA (Dolbeer et al., 2012, 2015, 2016, 2019, 2021). The most recent report (Dolbeer et al., 2021) presents a summary analysis of data from 1990 to 2019 in the FAA Wildlife Strike Database. The following characteristics of wildlife strikes are discussed in the report (Dolbeer et al., 2021).

- The number of wildlife strikes annually reported to the FAA increased 9.3-fold over the 30-year period. The number of wildlife strikes reported in 2019 was six percent greater than the number of wildlife strikes reported in 2018.

- Wildlife strikes are most likely to occur between July and November.
- Bird strikes occur more often during the day whereas terrestrial mammals are more likely to be struck at nighttime.
- In 2019, airport operation personnel reported 66 percent of the wildlife strikes, followed by pilots (15 percent) and air traffic controllers (11 percent).
- In 2019, commercial aircraft were involved in 86 percent of the wildlife strikes; the rest included business, private, and government aircraft.
- Over 70 percent of wildlife strikes occur at or below 500 feet. Strikes that occur above 500 feet are more likely to cause damage.
- Nearly twice the number of wildlife strikes occur during the arrival phase of flights compared to the departure phase.
- Precautionary or emergency landing and aborted take-off are the two most common negative effects on flights.
- On average over the 30-year period, eight percent of the reported wildlife strikes resulted in aircraft damage. The most common components damaged are the aircraft nose, windshield, wing, engine, and fuselage.

Runway Incursions Database and Research

Reducing runway safety risk is a top priority for the FAA (2018a, 2020e) and FAA has addressed runway incursions through runway safety technologies and the runway incursion mitigation (RIM) program. The RIM program was released by the FAA in 2015, and it has been used to identify, prioritize, and develop strategies to help airport sponsors mitigate risk at locations where airport geometry may be a factor that contributes to runway incursions.

Many studies on runway incursions have been based on data from the FAA RWS database. Wilke et al. (2015) proposed a framework for modeling causal factors of runway incursions and their relationship to severity through analyzing the events that occurred between October 2007 and December 2009. Findings suggest that the contribution of air traffic control (ATC) to high-severity runway incursions stands out; the numbers of runways, taxiways, and intersections are associated with the severity of runway incursions. Johnson at al. (2016) explored the relationship between airport geometry and runway incursions at the busiest airports from 2009 to 2013. The study found that the number of runway incursions is greater at airports with intersecting runways than at airports without intersecting runways. The number of crossing taxiways per runway and the number of runway intersections per runway are two significant factors that affect runway incursions. Mathew et al. (2017) analyzed runway incursions between 2001 and 2014 and identified factors affecting the severity of runway incursions by airport category and incident type. It was found that operational incidents that are caused by ATC errors are significant for both severity A (most severe) and severity C runway incursions at large hub airports, and vehicle/pedestrian deviations (VPD), which may be caused by airfield operation vehicles or personnel, have an increased probability of resulting in severity C or D (least severe) runway incursions. At medium and small hub airports, operational incidents are positively correlated with severity C runway incursions, and pilot deviations that are caused by pilot errors and VPD increase likelihoods of resulting in severity D runway incursions. At non-hub and GA airports, pilot deviations are a significant factor in causing severity C and D runway incursions, and VPD are more likely to result in severity D runway incursions.

The FAA RWS database was created in the 1990s (FAA, 2014) and contains records for all runway incursions in the USA from 2001 until the present time (FAA, 2020f). According to the FAA, the number of runway incursions has been increasing since 2012. A runway incursion report includes the following information: event date, category, type, airport name and code, type of aircraft involved, federal aviation regulation (FAR) part under which the aircraft was operated, weather condition, and the number of the runway at which the event occurred.

Methodology

Four FAA data sources were used in this study: the UAS Sightings Report database, the Wildlife Strike Database, the RWS database, and the Air Traffic Activity Data System, which contains airport operations data. This study examined UAS sightings occurring during the three-year period from September 2016 to August 2019; these dates were considered appropriate since FAR Part 107 went into effect on August 29, 2016. Wildlife strikes and runway incursions reported during the same period were studied and compared to UAS sightings.

UAS Sightings

UAS sighting reports analyzed in this study were obtained from the FAA's (2020a) UAS sighting database. UAS sighting reports generally provide information about the event date, time, city, state, and a narrative of the event. For each UAS sighting, the narrative was reviewed to identify the following information:

- UAS altitude
- Distance from the UAS sighting location to the nearby airport
- Nearby airport
- Whether a mandatory occurrence report alert was issued

- Law enforcement department(s) that was notified of the UAS sighting
- Source of the UAS sighting report
- Model of manned aircraft (if involved)
- UAS-to-manned aircraft proximity
- Distance between UAS and manned aircraft
- Whether evasive action was taken by the pilot(s) of the manned aircraft

The method for analyzing UAS sightings in this study is similar to the method used by UAST (2017). Researchers (Wang & Hubbard, 2022) reviewed UAS sighting reports to extract information about 10 selected criteria, shown in Table 3, which shows the methodology for analysis of the narrative in UAS sighting reports. This methodology provides reliable and potentially actionable insights to enhance the veracity and informative nature of UAS sighting reports.

Data Summary

Table 4 provides an overview of the data used to compare the airport risks investigated in this paper. Table 4(a) shows the number of each airport risk by year; Table 4(b) displays the characteristics of each airport risk that are compared in this study.

Results and Discussion

This section presents the results of the comparisons of UAS sighting data with data related to wildlife strikes and runway incursions. Comparisons between UAS and wildlife strike data are presented first, followed by comparisons between UAS and runway incursion data. Finally, the data are examined in the context of the airports to which they relate.

Temporal Distribution: UAS Sightings and Wildlife Strikes

Between January 1, 2015, and December 31, 2019, a total of 9,552 UAS sightings were recorded. This is similar to the number of reports for wildlife strikes recorded in the first four years of the wildlife strike database (FAA collected 9,045 wildlife strike reports from 1990 through 1993). Expanding wildlife populations, increases in number of aircraft movements, a trend toward faster and quieter aircraft, and outreach to the aviation community about the database all have contributed to the observed increase in reported wildlife strikes. Figure 1 shows the number of UAS sighting reports and wildlife strike reports by year. There is a similar trend for UAS sightings and wildlife strikes in that the number of reports increased dramatically in the second year, and then slowly increased in the next few years.

UAS sightings and wildlife strikes also vary by time of year, as shown in Figure 2. Most UAS sightings are reported between May and July, whereas wildlife strikes peak from July to October. Both threats taper off in winter (wildlife strikes more dramatically) and begin to resume in spring. The distribution of UAS sightings is likely due to increased UAS flights in the summer months and increased GA traffic in the summer months (Mathew et al., 2017). Wildlife strikes are most common in summer and fall, which are the wildlife migratory seasons (Aircraft Owners and Pilots Association, n.d.).

UAS sightings and wildlife strikes also vary by time of day. As shown in Figure 3(a), the majority of UAS

Table 3
Identification and analysis of narrative in UAS sighting reports.

Goal	Format	Methodology
To determine the UAS altitude in feet above ground level (AGL).	Numeric with no special characters or "unknown."	No assumptions are made. If the report states, "drone passed above aircraft," it is listed as unknown.
To determine the distance between the location of UAS sighting and the airport in nautical miles.	Numeric with no special characters or "unknown."	No assumptions are made. If the report states, "EASTBOUND OVER REDWOOD ROAD EAST OF SALT LAKE CITY ARPT," it is listed as unknown.
To determine the airport that is close to the location of UAS sighting.	In text, FAA's airport code or "unknown."	Narratives including specific airport that was close to the location of the UAS sighting. Exemplary statement: "2 NE SLC."
To determine whether a MOR was filed.	"Yes" or "no."	The narrative indicates that a MOR was filed.
To determine whether law enforcement department(s) was notified of the UAS sighting.	"Yes," "no," or "unknown."	Narratives including specific department(s) that was notified of the UAS sighting are classified as "yes." A report that states, "LEO NOTIFICATION NOT REPORTED," is listed in "no." An example of "unknown": "LEO NOTIFICATION UNKN."
To determine the source of the UAS sighting.	In text, "airport," "ATC," "citizen," "LEO," "military," "passenger," "pilot," "other," or "unknown."	Exemplary statements: "U.S. PARK POLICE REPORTED SEEING A UAS," and "A PASSENGER SIGHTED A UAS."
To determine the model of manned aircraft involved in the UAS sighting.	In text, "commercial," "GA," "helicopter," "military," "no aircraft involved," or "unknown."	The type of manned aircraft involved in the UAS sighting is stated in the narrative.

Table 4(a)
Summary data for airport risks.

Time[a]	Number of reports by airport risk		
	UAS sighting	Wildlife strike	Runway incursion
September–December 2016	534	4,927	786
2017	2,121	15,071	2,420
2018	2,303	16,435	1,773
January–August 2019	1,586	11,141	1,062
Total	6,551[b]	47,574	6,041[c]

[a]Characteristics of UAS sightings discussed in the results section are based on the three-year period, excluding Figure 1(a) that reflects the number of UAS sightings reported from 2015 to 2019. [b]Seven reports in the UAS Sighting Database were excluded, because they involved something other than a drone. [c]There are 6,041 events in the RWS database, but only 5,148 events that were categorized as severity A, B, C, or D runway incursions were included.

Table 4(b)
Comparisons of airport risks.

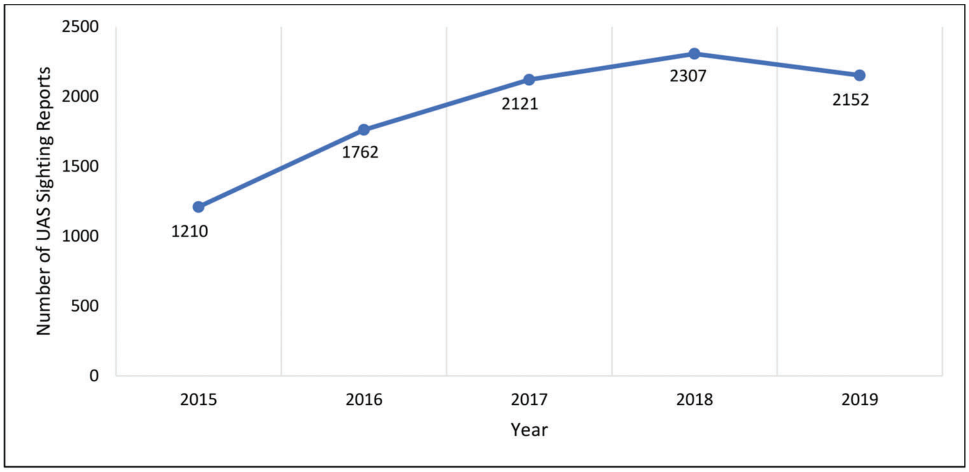
Airport risks	Characteristics compared
UAS sighting and wildlife strike	• Temporal distribution (yearly, monthly, and hourly trend) • Spatial distribution (altitude, distance from the airport)
UAS sighting and runway incursion	• Severity (as indicated by the need for evasive action) • Type of aircraft operation
UAS sighting, wildlife strike, and runway incursion	• Events by National Plan of Integrated Airport Systems (NPIAS) airport category • Airport rank by number of events and rate (number of events normalized by number of airport operations)

sightings occur during the daytime, with 70.8 percent between 11 a.m. and 6 p.m. local time. This is consistent with FAR Part 107 which does not allow UAS operations from dusk to dawn (although the FAA does grant waivers). This figure also reflects trends in both commercial and GA flights; most commercial flights are between 7 a.m. and midnight; GA flights are most common during daylight hours. The distribution of wildlife strikes by time of day is slightly different from that of UAS sightings. As shown in Figure 3(b), the peak hours for wildlife strikes are in the morning, continuously from 7 a.m. to noon, representing 39.7 percent of all wildlife strikes, which is consistent with bird feeding activity in the morning (SKYbrary, 2020). This result is consistent with previous research by Dolbeer et al. (2012).

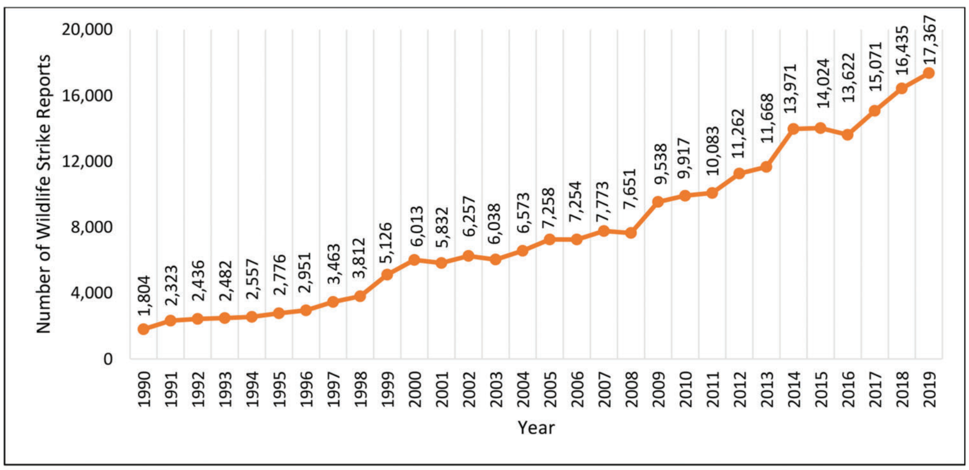
Spatial Distribution: UAS Sightings and Wildlife Strikes

Airport operators are interested in UAS that are in the proximity of the airport and may potentially affect airport operations and the safety of taking off and landing flights. Figure 4(a) shows UAS sightings by altitude and distance from the airport. Generally, UAS sightings farther from airports occur at higher altitudes than UAS sightings close to airports, which is reasonable since aircraft tend to be at higher altitudes when they are farther from airports. The average altitude of UAS sightings farther than 10 miles from the airport is 6,076 feet, which is within the altitude range of flights under visual flight rules; the average altitude of UAS sightings within 10 miles of the airport is 2,692 feet, which is higher than the usual traffic pattern altitude at 1,000 feet above ground level. Most of the UAS sightings are reported flying within 30 miles of an airport and below 10,000 feet. There are 56 data points missed in Figure 4(a), which are UAS sightings occurring at airports or reported zero altitude.

Figure 4(b) shows 3,596 wildlife strikes by altitude and distance from the airport. Although 14,115 wildlife strike reports include both altitude and distance from the airport, 10,519 of these reported that wildlife strikes occurred at airports or reported zero altitude. Wildlife strikes reported at zero altitude were assumed to be from terrestrial mammals on the ground, hence analogous to UAS ground operations which were out of scope. The trend of altitude and distance from the airport for wildlife strikes is the same as the trend for UAS sightings. Wildlife strikes that occur more than 10 miles from an airport are reported at higher altitudes than wildlife strikes within 10 miles of an airport. The average altitude of wildlife strikes with a recorded airport distance of more than 10 miles is 5,302 feet, which is within the altitude range of flights under visual flight rules; the average altitude of UAS sightings within 10 miles of an airport is 403 feet, which is lower than the usual traffic pattern altitude at 1,000 feet above ground level. Most of the wildlife strikes are reported flying within 10 miles of an airport and below 10,000 feet.



(a) UAS sighting reports



(b) Wildlife strike reports

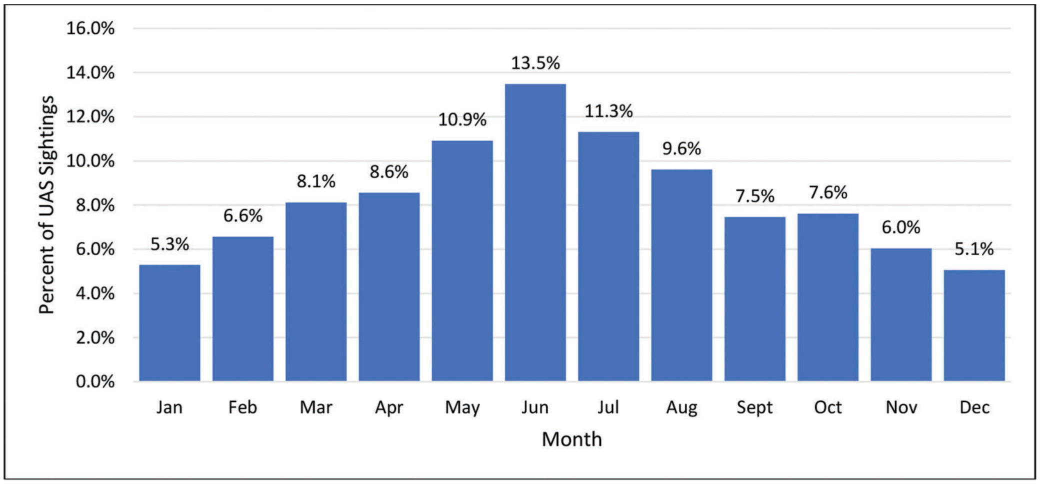
Figure 1. Distribution of UAS sighting reports and wildlife strike reports by year.

In terms of altitude, of the 87 percent of UAS sighting reports that include an altitude, 91 percent of UAS sightings occur above the maximum altitude of 400 feet per FAR Part 107, although UAS operations may have been issued to fly in the vicinity of an airport or above 400 feet of the ground in some cases. This reflects a lack of compliance with the FAA's rule. The highest recorded altitude for a UAS sighting is 39,000 feet, and the average altitude is 3,355 feet. Figure 5(a) shows the distribution of UAS sightings by altitude, excluding UAS sightings that report the altitude is zero.

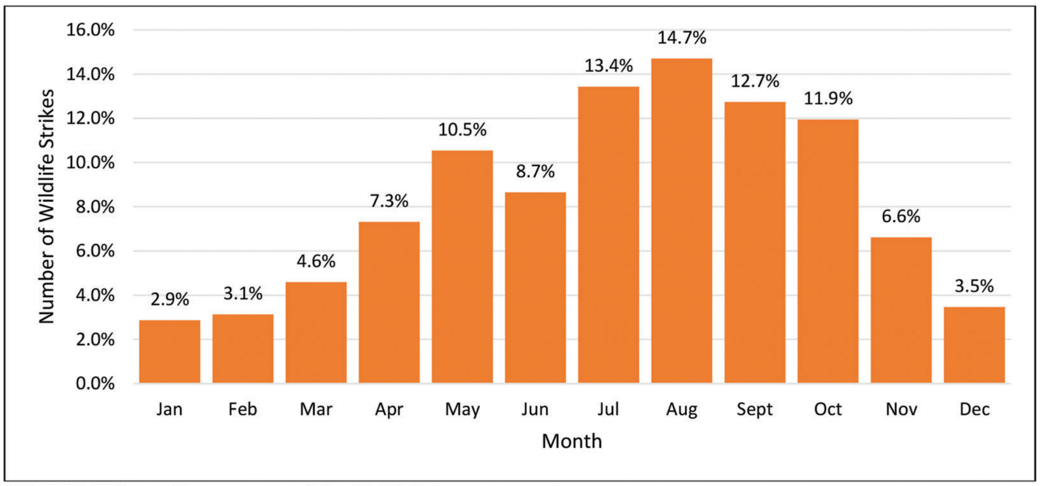
Figure 5(b) shows the distribution of wildlife strikes by altitude, excluding events that report the altitude is zero. From September 2016 to August 2019, there are 19,934 reported wildlife strikes for which the altitude is provided, which represent 41.9 percent of all wildlife strikes. Based on the analysis of wildlife strike reports, 65.9 percent of these events occur within 400 feet of the ground. The highest recorded altitude for a wildlife strike is 23,000 feet, and the average altitude is 906 feet. The first and the third quartile indicate that more than 25 percent of wildlife strikes occur at ground level and most of the events occur at low altitudes. In general, altitudes of UAS sightings are higher than altitudes of wildlife strikes.

In terms of distance from the airport, for the 72 percent of UAS sightings for which the distance from an airport is recorded, 57 percent occurred within five miles of the reported airport; 83 percent occurred within 10 miles from the reported airport; 99 percent occurred within 30 miles of the airport. The average distance from an airport is 6.94 miles. It is notable that a few UAS sightings occur up to 180 miles from the reported airport. UAS sightings that are reported more than 50 miles from an airport may reflect the nearest commercial airport or the airport where the aircraft took off or planned to land, rather than the nearest airport on the NPIAS. Figure 6(a) shows the distribution of UAS sightings by distance from the airport, excluding UAS sightings that report the distance is zero.

Figure 6(b) shows the distribution of wildlife strikes by distance from the airport, excluding events that report the



(a) UAS sighting reports (N=6,544)



(b) Wildlife strike reports (N=47,575)

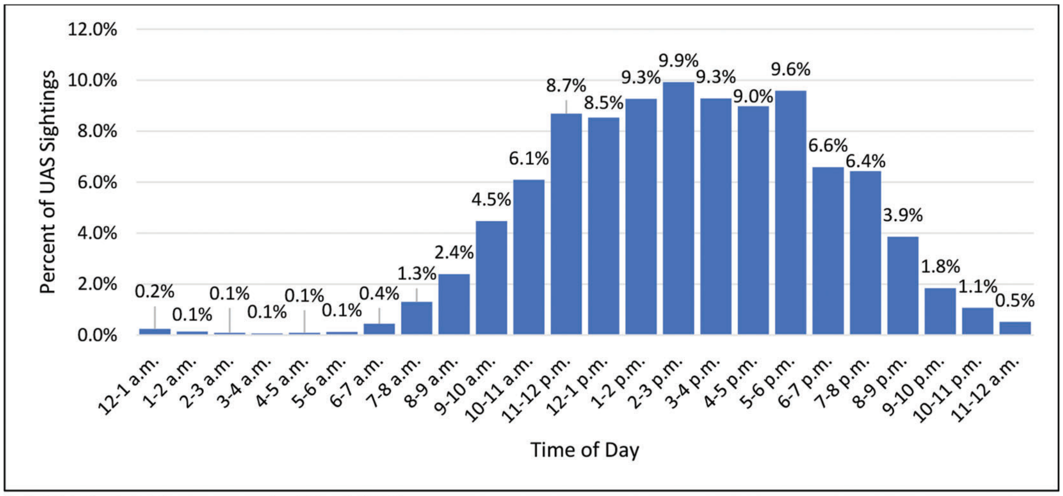
Figure 2. Distribution of UAS sighting reports and wildlife strike reports by month.

distance is zero. For the three-year period, 89.5 percent of wildlife strikes occur within one mile of the reported airport; 94.9 percent occur within five miles of the reported airports; 97.7 percent occur within 10 miles of the reported airport; 99.8 percent occur within 30 miles of the airport. The average distance from an airport is 0.89 mile. The third quartile distance indicates that over 75 percent of wildlife strikes occur in the airport and wildlife strikes occur close to airports. In general, distances of UAS sightings from the airport are farther than the distances of wildlife strikes from the airport.

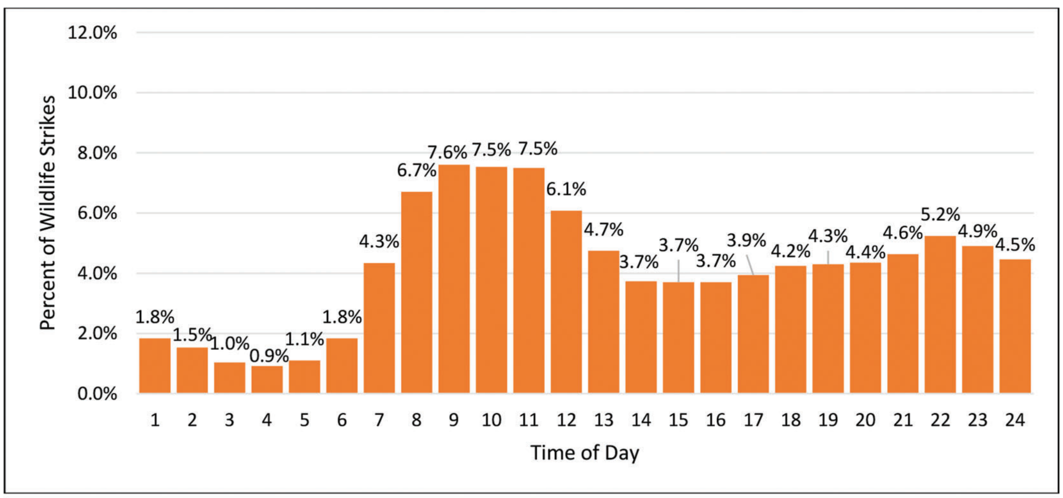
Severity and Type of Aircraft Operations: UAS Sightings and Runway Incursions

It is helpful to compare UAS sightings with runway incursions in terms of severity and type of operation. For a UAS sighting, severity is reflected by the need for the pilot of a manned aircraft to take an evasive action to avoid a UAS. Fortunately, pilots rarely have to take evasive action to avoid UAS. As shown in Figure 7, which shows the severity of UAS sightings and runway incursions, pilots take evasive action in only 3.3 percent of UAS sightings (210 UAS sightings require evasive action). The need for evasive action is affected by a number of factors, including: distance between the UAS and aircraft, whether the UAS is stationary or moving toward or flying away from the aircraft, whether there is time to take evasive action, and the type of aircraft and the type of UAS.

For runway incursions, severity is categorized from A (most severe) to D (least severe). The need for an evasive maneuver to avoid a UAS may be somewhat analogous to a category A or category B runway incursion. According to the FAA (2020g), a category A runway incursion is defined as a serious incident in which a collision was narrowly avoided; a category B runway incursion has a significant potential for collision and requires a time-critical evasive response to avoid a collision. As shown in Figure 7(b), 0.6 percent of runway incursions are categorized as category A or category B.



(a) UAS sighting reports (N=6,530)



(b) Wildlife strike reports (N=29,743)

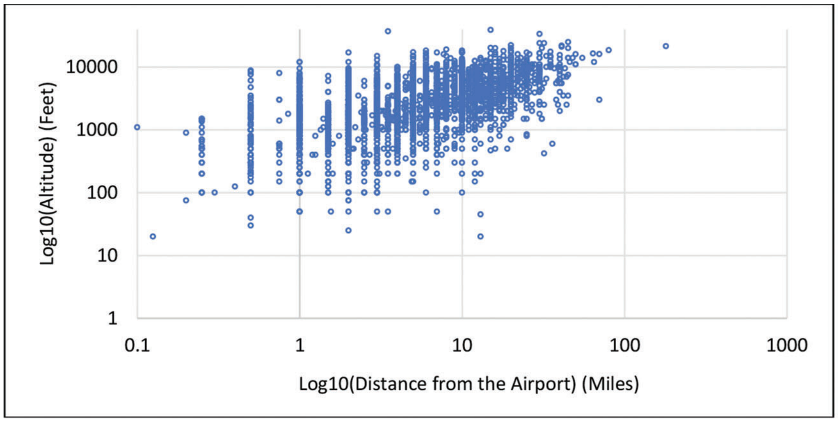
Figure 3. Distribution of UAS sighting reports and wildlife strike reports by time of day.

The comparison suggests that the need for an evasive maneuver is higher for UAS sightings. This may be affected by the likelihood of reporting a non-hazardous or low-hazard event. Reporting low-hazard runway incursions may be higher, and pilots and air traffic controllers may be more likely to report a category D runway incursion than a UAS sighting that is of no threat. More reporting may also be due to familiarity with the database and legal requirements for reporting runway incursions.

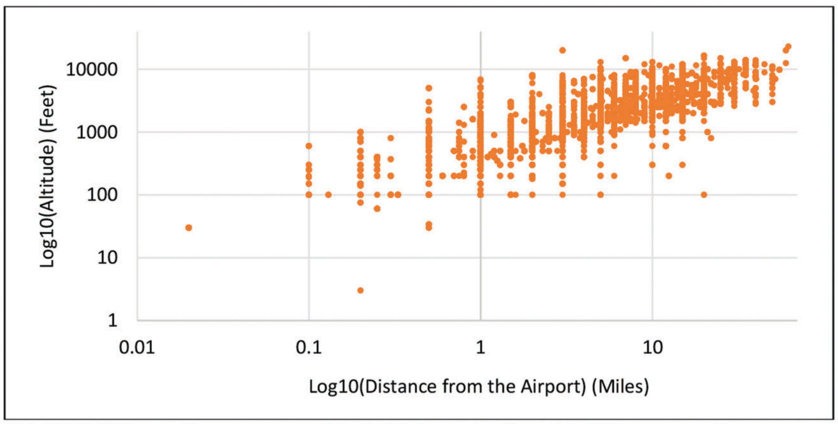
It is also helpful to consider the type of aircraft operations affected. All kinds of aircraft may be affected by UAS sightings, and pilots who fly a wide variety of aircraft have filed UAS sighting reports. Pilots of GA aircraft (such as a Cessna 172) and business jets (such as a Hawker 400) report the most UAS sightings, representing 43.3 percent of the reports, as shown in Figure 8(a). Large commercial aircraft (such as A320 and CRJ 700) are also affected by UAS sightings, and account for 37.6 percent of the UAS sightings. Although rare, commercial flight operations disrupted by UAS sightings may result in flight delays, diversions, cancelations, closure of runways, or even airport closure.

The high number of UAS sightings reported by pilots of GA aircraft is more striking when the operational mix is considered. GA operations account for only 16 percent of operations as shown in Figure 8(b) but comprise 43.3 percent of UAS sightings. This may be due to the lower altitudes of GA flights. In contrast, commercial operations account for 80.1 percent of all operations, although only 37.6 percent of UAS sightings involve commercial aircraft. This may be due to the fact that most commercial flights fly above the altitude of UAS, and certainly above the altitude of UAS operating under FAR Part 107, which mandates a maximum altitude of 400 feet.

GA operations account for the largest share of UAS sightings and are also involved in more runway incursions. As shown in Table 5, which shows the number of runway incursions by operation type and runway incursion category, 60 percent of runway incursions involve at least one aircraft operating under Part 91, and about two-thirds



(a) UAS sighting reports (N=4,383, excluding 56 events that report the altitude is zero or occurred at airports)



(b) Wildlife strike reports (N=3,596, excluding 10,519 events that report the altitude is zero or occurred at airports)

Figure 4. Distribution of reports by altitude and distance from the airport.

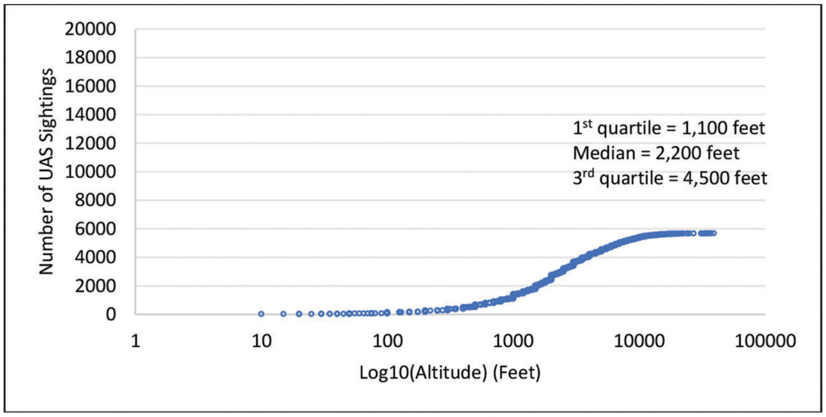
of category A and category B runway incursions involve at least one aircraft operating under Part 91. In contrast, only 25 percent of runway incursions involve at least one commercial aircraft operating under FAR Part 121, Part 125, Part 129, or Part 135 (FARs for commercial operations) and commercial aircraft account for one-third of category A and category B runway incursions. Overall, GA aircraft are at greater risk for both runway incursions and UAS sightings relative to commercial aircraft.

Table 6 shows the number and rate of UAS sightings by operation type and the need for evasive action. GA aircraft and helicopters are more likely to take evasive action than commercial aircraft, which may be due to the altitudes at which they commonly fly, the lower speeds at which they travel, their ability to change course quickly, and their vulnerability to damage if there is a collision with a drone.

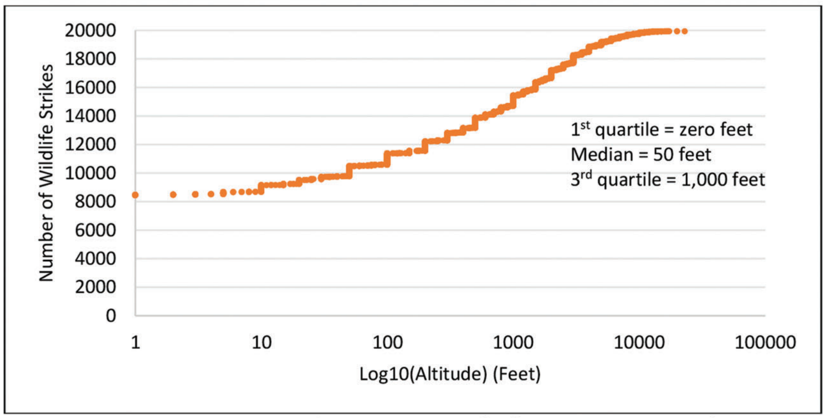
NPIAS Airport Category: UAS Sightings, Wildlife Strikes, and Runway Incursions

This section discusses the incidence of UAS sightings, wildlife strikes, and runway incursions for different NPIAS airport categories. These categories are generally based on the number of enplanements, or passengers that board aircraft at the airport. NPIAS (FAA, 2018b) airports are categories as primary and nonprimary. Primary airports include: large hub, medium hub, small hub, and non-hub airports; nonprimary airports include: commercial service airports, GA airports, and reliever airports, a special category of GA airports near large and medium hub airports.

The number of UAS sightings per airport differs depending on the airport category. Primary airports only account for 11.4 percent of NPIAS airports; however, 67 percent of UAS sightings occur at primary airports. Figure 9(a) and Figure 9(b) show the distribution of airports and UAS sightings by airport category. UAS sightings are more common at primary airports, especially large and medium hub airports. Although large and medium hub airports only account for 1.8 percent of NPIAS airports, 48.9 percent of UAS sightings occur and large and medium hub airports. Between September 2016 and August 2019, all large and medium hub airports had at least one UAS sighting; 66 (91.7 percent) small hub airports also had at least one UAS



(a) UAS sighting reports (N=5,659, excluding 23 events that report the altitude is zero)



(b) Wildlife strike reports (N=11,496, excluding 8,438 events that report the altitude is zero)

Figure 5. Cumulative distribution by altitude.

sighting. Closure of a large or medium hub airport due to a UAS sighting would be very disruptive since these 61 airports serve over 88 percent of all passenger trips (FAA, 2018b).

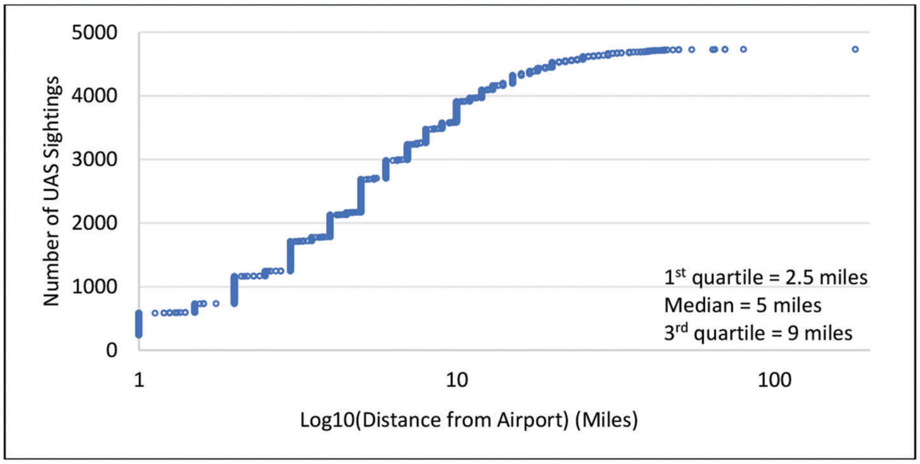
Similar to UAS sightings, the number of wildlife strikes varies by airport category, and wildlife strikes are more common at primary airports. Figure 9(c) shows the distribution of wildlife strikes by airport category. Seventy-four percent of wildlife strikes occur at the 380 primary airports, including 32.2 percent of wildlife strikes at large and medium hub airports. Between September 2016 and August 2019, all 30 large hub airports had at least one wildlife strike; 29 of 31 medium hub airports, 67 of 72 small hub airports, and 214 of 247 nonhub airports had at least one wildlife strike. Wildlife strikes are less common at nonprimary airports, which account for only 9.6 percent of wildlife strikes, though these airports make up 88.6 percent of NPIAS airports and 64.3 percent of total aircraft operations (FAA, 2018b).

Runway incursions are more likely to occur at smaller airports, especially reliever airports. As shown in Figure 9(d), 30.7 percent of runway incursions occur at reliever airports, although only 7.9 percent of airports in the NPIAS are categorized as reliever airports. Reliever airports are not equally affected by runway incursions, since fewer than half reported runway incursions. The top 10 reliever airports account for 9.5 percent of all runway incursions, and all of these have at least one location included in the FAA's RIM inventory (FAA, 2020h). Comparing with UAS sightings and wildlife strikes, runway incursions are less often reported at large and medium hub airports.

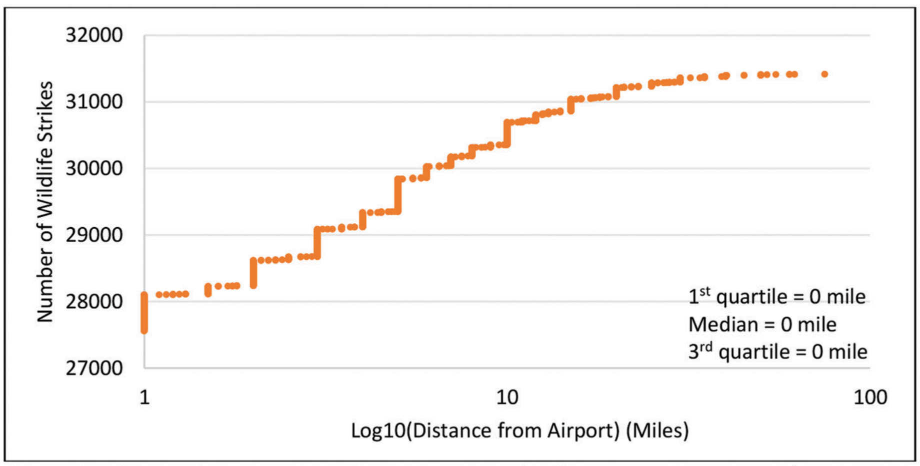
Airport Rank: UAS Sightings, Wildlife Strikes, and Runway Incursions

This section presents airport rankings for each risk by number of events and rate. In general, UAS sightings and wildlife strikes are more common at primary airports whereas runway incursions are more common at reliever airports.

Table 7(a) presents the number of UAS sighting reports at the top 20 airports, which are all large hub airports. The greater number of UAS sightings at large hub airports may be partially explained by the geographic characteristics. Most large hub airports are located in or close to big cities that have large populations and high population densities;

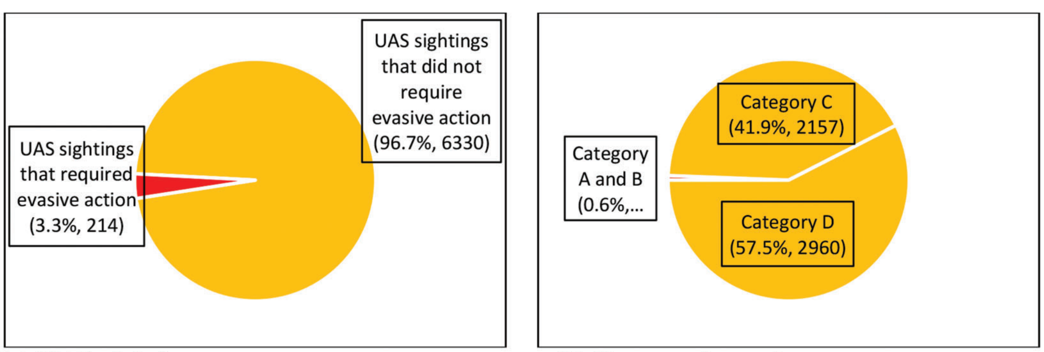


(a) UAS sighting reports (N=4,647, excluding 84 events that occurred at airports)



(b) Wildlife strike reports (N=4,234, excluding 27,179 events that occurred at airports)

Figure 6. Cumulative distribution by distance from the airport.



(a) UAS sighting reports **(b) Runway incursions**

Figure 7. Distribution of reports by severity.

higher population and population density may contribute to the increased frequency of UAS sightings in these cities. As shown in Table 7(a), the top five airports with the most UAS sightings (LGA, LAX, JFK, ORD, EWR) are close to the three largest cities in terms of population. The top three airports also had the highest number of reports when normalized with respect to annual airport operations.

Table 7(b) shows the top 10 airports that reported the most wildlife strikes, including eight large hub airports and two medium hub airports. Seven airports that are in the top 10 for wildlife strikes are also in the top 20 for UAS sightings. DTW is the only large hub airport ranked in the top 10 airports for wildlife strikes but not in the top 20 airports for UAS sightings. This may be due to the airport's

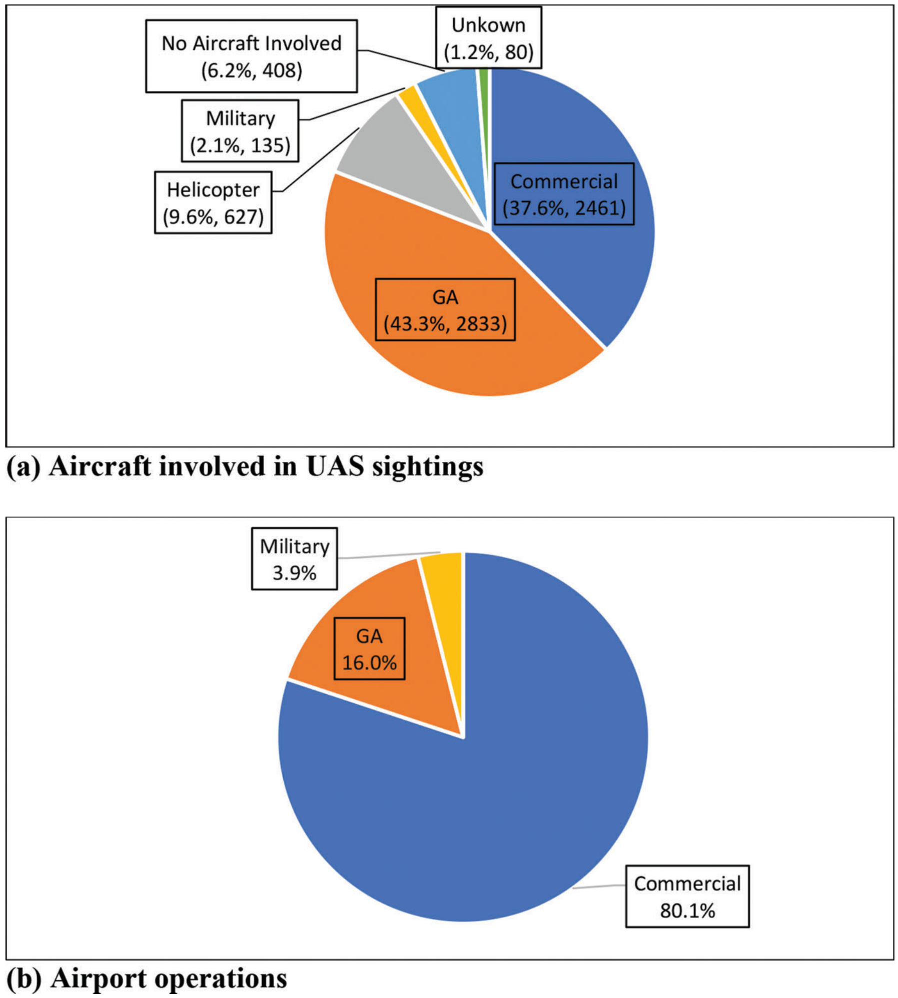


Figure 8. Distribution of reports by operation type.

Table 5
Runway incursion reports by operation type and category, from September 2016 to August 2019.

		Aircraft 2 flight condition code				
Aircraft 1 flight condition code	**Category**	**Part 91**	**Part 121, 125, 129, or 135**	**Other**	**Military**	**N/A**
GA operations (Part 91)	A and B	11				
	C and D	956				
Commercial operations	A and B	2	5			
(Part 121, 125, 129, or 135)	C and D	341	775			
Other	A and B	0	0	0		
	C and D	7	11	0		
Military	A and B	2	1	0	0	
	C and D	39	13	0	4	
N/A	A and B	1	1	0	0	0
	C and D	1,613	219	19	34	0
Pedestrian or vehicle	A and B	3	4	0	0	1
	C and D	162	135	0	10	639
Total	A and B	19	11	0	0	1
	C and D	3,118	1,293	19	48	639

large geographic area, a concept supported by the relatively low rank and rate of DEN, which is the largest airport in terms of acreage.

Table 7(c) shows the top 10 airports with the most runway incursions, which reflects a wide range of airport categories and includes six large hub airports, one medium

Table 6
UAS sighting reports by operation type and need for evasive action.

Number of UAS sightings	Total	GA aircraft	Commercial aircraft	Helicopter	Military aircraft	Aircraft type unknown
UAS sightings that required evasive action	210	127	16	60	7	0
UAS sightings that did not require evasive action	5,925	2,706	2,445	567	128	80
Events reported that required evasive action	1 : 28.2 (3.4%)	1 : 21.3 (4.5%)	1 : 152.8 (0.65%)	1 : 9.5 (9.6%)	1 : 18.3 (5.2%)	

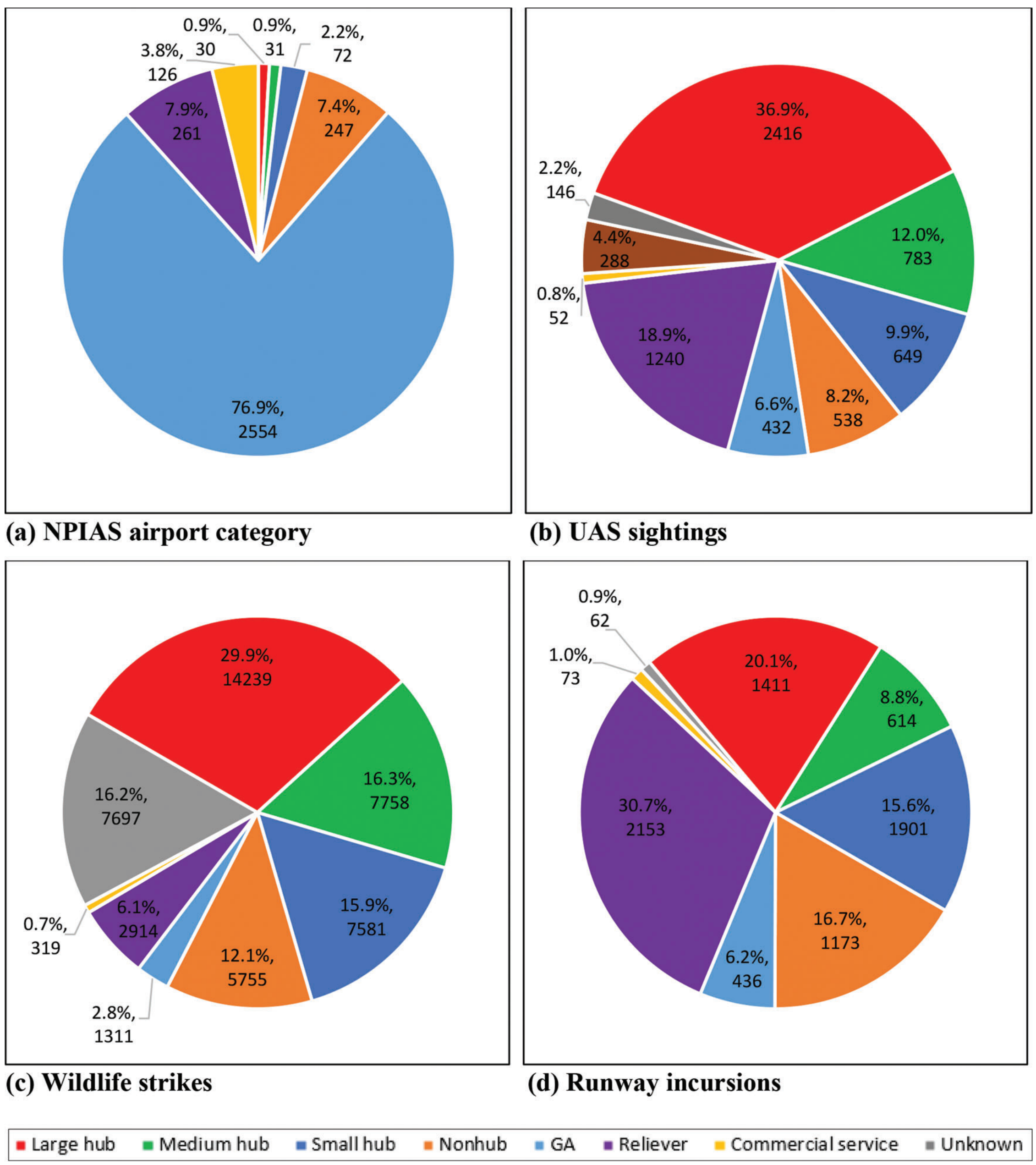


Figure 9. Distribution of reports by airport category.

Table 7(a)
Airports with the most UAS sightings (top 20).

		UAS sightings					Location of airport		Rank for other threats (based on number of events)	
Rank	Airport code	Number	Airport category	Annual operations	Rate (per 10,000 operations)	Rank by rate	Nearby city	State	Wildlife strikes	Runway incursions
1	LGA	311	Large hub	369,632	8.41	1	New York	New York	12	
2	LAX	210	Large hub	701,969	2.99	10	Los Angeles	California	17	3
3	JFK	157	Large hub	458,421	3.42	7	New York	New York	7	
4	ORD	116	Large hub	887,475	1.31		Chicago	Illinois	4	1
5	EWR	112	Large hub	446,301	2.51	20	New York	New Jersey	16	
6	MIA	98	Large hub	414,997	2.36		Miami	Florida		
7	LAS	92	Large hub	543,164	1.69		Las Vegas	Nevada		16
8	DCA	89	Large hub	297,829	2.99	11	Washington, DC	Virginia		
9	ATL	86	Large hub	892,810	0.96		Atlanta	Georgia	5	17
10	IAH	83	Large hub	462,716	1.79		Houston	Texas	19	
11	BOS	81	Large hub	417,915	1.94		Boston	Massachusetts		5
12	PHL	78	Large hub	378,787	2.06		Philadelphia	Pennsylvania		
13	CLT	76	Large hub	555,345	1.37		Charlotte	North Carolina	8	8
14	MCO	75	Large hub	347,938	2.16		Orlando	Florida	10	
15	DFW	74	Large hub	671,799	1.10		Dallas/Fort Worth	Texas	2	18
16	SEA	68	Large hub	429,937	1.58		Seattle	Washington		15
17	FLL	66	Large hub	321,509	2.05		Miami	Florida		
18	DEN	64	Large hub	600,529	1.07		Denver	Colorado	1	
19	PHX	61	Large hub	432,659	1.41		Phoenix	Arizona		
20	SFO	61	Large hub	463,597	1.32		San Francisco	California		7

Table 7(b)
Airports with the most wildlife strikes (top 10).

	Wildlife strikes						Rank for other threats (based on number of events)	
Rank	**Airport code**	**Number**	**Airport category**	**Annual operations**	**Rate (per 10,000 operations)**	**Top 20 by rate**	**UAS sightings**	**Runway incursions**
1	DEN	1,288	Large hub	600,529	21.45		18	
2	DFW	1,064	Large hub	671,799	15.84		15	18
3	DTW	1,042	Large hub	394,394	26.42	19		6
4	ORD	861	Large hub	887,475	9.70		4	1
5	ATL	824	Large hub	892,810	9.23		9	17
6	MEM	768	Medium hub	226,005	33.98	8		
7	JFK	703	Large hub	458,421	15.34		3	
8	CLT	649	Large hub	555,345	11.69		13	8
9	MCI	554	Medium hub	125,005	44.32	1		
10	MCO	535	Large hub	347,938	15.38		14	

Table 7(c)
Airports with the most runway incursion reports (top 10).

	Runway incursions						Rank for other threats (based on number of events)	
Rank	**Airport code**	**Number**	**Airport category**	**Annual operations**	**Rate (per 100,000 operations)**	**Top 20 by rate**	**UAS sightings**	**Wildlife strikes**
1	ORD	137	Large hub	887,475	1.54		4	4
2	CNO	111	Reliever	201,691	5.50	15		
3	LAX	90	Large hub	701,969	1.28		2	17
4	DVT	86	Reliever	410,561	2.09			
5	BOS	82	Large hub	417,915	1.96		11	
6	DTW	82	Large hub	394,394	2.08			3
7	SFO	81	Large hub	463,597	1.75		20	
8	CLT	76	Large hub	555,345	1.37		13	8
9	HOU	73	Medium hub	203,370	3.59			
10	BOI	72	Small hub	132,086	5.45	17		
	TUS	72	Small Hub	131,660	5.47	16		

hub airport, two small hub airports, and two reliever airports. Only five of the top ten airports that had the most runway incursions are in the top 20 airports for UAS sightings. This suggests that the factors that contribute to UAS sightings and runway incursions are different. The reason for more runway incursions at reliever airports may be due to their function. Reliever airports are mainly used to relieve congestion at commercial service airports, and to provide GA access to the community. GA operations correlate with increased runway incursions, and unfamiliar pilots that come from the primary airport may be less familiar with the airport layout, both factors that may increase the likelihood of pilot deviations.

Conclusions

UAS sightings have become an increasing concern for the aviation community. This research analyzes the characteristics of UAS sightings and compares them with two well-known airport threats, wildlife strikes and runway incursions, and suggests there are some similarities and some differences for these three airport threats.

Considering UAS sightings and wildlife strikes, both vary by time of year and time of day. Both UAS sightings and wildlife strikes farther from an airport occur at higher altitudes than those closer to an airport, although UAS sightings are reported at higher altitudes than wildlife strikes, and generally occur farther from airports than wildlife strikes. Considering UAS sightings and runway incursions, the severity of these events tends to be similar and fortunately severe events for both incidents are rare. Pilots take evasive actions in only three percent of UAS sightings, and runway incursions of severity A and B are very rare (less than one percent). Pilots of GA aircraft report the most UAS sightings, and GA operations are involved in more runway incursions than other types of flight. In terms of the characteristics of the affected airports, UAS sightings and wildlife strikes are more common at primary airports whereas runway incursions are more common at smaller reliever airports.

This research demonstrates the value of UAS sighting reports, which provide an in-depth and comprehensive understanding of UAS sightings and their impacts on airports, and is one way to advance research and increase safety in the aviation sector. Given the value of UAS sightings and the database, it is recommended that the FAA simplify the UAS sighting reporting procedure and create an online reporting system that is analogous to the FAA Wildlife Strike Database, rather than requiring reports to be filed through the Flight Service District Office. An online reporting system could potentially expand the impact of the database.

This research presents UAS sightings in the context of much more familiar events, wildlife hazards and runway incursions. Future research could investigate the similarities and differences among these three airport threats by using statistical methodologies to correlate characteristics, as well as track changes in characteristics over time. Fortunately, UAS have had a minimal impact on airport operations despite their growing prevalence, which reflects the overall success of integrating this new airspace user into the national airspace system.

References

ABC News. (2020, February 3). *Drone sighting disrupts air traffic at Madrid airport*. Retrieved from https://abcnews.go.com/International/wireStory/spain-closes-airspace-madrid-airport-drones-reported-68719452

Academy of Model Aeronautics. (2016). *An analysis of the FAA's March 2016 UAS sightings*. Retrieved from http://amablog.modelaircraft.org/amagov/files/2016/06/AMA-Analysis-FINAL-6-1-16.pdf

Academy of Model Aeronautics. (2017). *As drone sales soar, vast majority of reports remain simple sightings*. Retrieved from https://www.modelaircraft.org/sites/default/files/UASSightingsAnalysisbyAMA5-10-17.pdf

Aena. (2020, September 15). *Relevant figures*. Retrieved from http://www.aena.es/en/corporate/relevant-figures.html

Aircraft Owners and Pilots Association. (n.d.). *Bird and wildlife strikes*. Retrieved from https://www.aopa.org/training-and-safety/active-pilots/safety-and-technique/bird-and-wildlife-strikes

Aratani, L. (2019, January 24). Maybe the drone that snarled Newark airport operations wasn't a drone at all. *Chicago Tribune*. Retrieved January 21, 2021, from https://www.chicagotribune.com/business/ct-biz-newark-drone-could-be-balloon-space-junk-20190124-story.html

British Broadcasting Corporation. (2019, July 12). *Flights diverted as drone sighted near Leeds Bradford airport*. Retrieved from https://www.bbc.com/news/uk-england-leeds-48967944

Burley & Menston Airport discussion. (2020, March). *Leeds Bradford airport—Latest passenger numbers March 2020*. Retrieved from http://www.haveyoursayatlba.co.uk/leeds-bradford-airport-latest-passenger-numbers-march-2020/

Changi Airport Group. (2020, August 20). *Air traffic statistics*. Retrieved from https://www.changiairport.com/corporate/our-expertise/air-hub/traffic-statistics.html#aem-ajaxpopup

Cohen, J. (2019, January 22). *Reported drone sightings cause flights to halt at Newark airport* [Webpage]. Retrieved January 21, 2021, from https://www.nj.com/essex/2019/01/reported-drone-sightings-cause-flight-delays-at-newark-airport.html

D'Souza, K., Lyons, T., Lacy, T., & Kota, K. R. (2017). *Volume IV—UAS airborne collision severity evaluation—Engine ingestion*. Federal Aviation Administration. Retrieved from https://www.assureuas.org/projects/deliverables/a3/Volume%20IV%20-%20UAS%20Airborne%20Collision%20Severity%20Evaluation%20-%20Engine%20Ingestion.pdf

Dolbeer, R. A. (2011, February 17). *A history of wildlife strikes and bird strike committee-USA*. [PowerPoint slides]. Bird Strike Committee-USA. Retrieved from http://www.birdstrike.org/wp-content/uploads/2014/10/History-BSC-USA-Dolbeer_WashingtonDC_Feb2011.pdf

Dolbeer, R. A., Begier, M. J., Miller, P. R., Weller J. R., & Anderson, A. L. (2019). *Wildlife strikes to civil aircraft in the United States, 1990-2018*. Federal Aviation Administration, Office of Airport Safety and Standards. Retrieved from https://www.faa.gov/airports/airport_safety/wildlife/media/Wildlife-Strike-Report-1990-2018.pdf

Dolbeer, R. A., Begier, M. J., Miller, P. R., Weller J. R., & Anderson, A. L. (2021). *Wildlife strikes to civil aircraft in the United States, 1990-2019*. Federal Aviation Administration, Office of Airport Safety and Standards. Retrieved from https://www.faa.gov/airports/airport_safety/wildlife/media/Wildlife-Strike-Report-1990-2019.pdf

Dolbeer, R. A., Weller J. R., Anderson, A. L., & Begier, M. J. (2016). *Wildlife strikes to civil aircraft in the United States, 1990-2015*. Federal Aviation Administration, Office of Airport Safety and Standards. Retrieved from https://lessonslearned.faa.gov/S76/Wildlife_Strike_Report.pdf

Dolbeer, R. A., Wright, S. E., Weller, J. R., Anderson, A. L., & Begier, M. J. (2015). *Wildlife strikes to civil aircraft in the United States, 1990-2014*. Federal Aviation Administration, Office of Airport Safety and Standards. Retrieved from https://rosap.ntl.bts.gov/view/dot/7548

Dolbeer, R. A., Wright, S. E., Weller, J. R., & Begier, M. J. (2012). *Wildlife strikes to civil aircraft in the United States, 1990-2011*. Federal Aviation Administration, Office of Airport Safety and Standards. Retrieved from https://www.faa.gov/airports/airport_safety/wildlife/resources/media/bash90-11.pdf

Dow, J. (2019, January 23). *Here's what happens when drones get near airports* [Webpage]. Retrieved January 21, 2021, from https://pix11.com/2019/01/23/heres-what-happens-when-drones-get-near-airports/

Dubai Airports. (2019, December 24). *Dubai airports*. Retrieved from https://www.dubaiairports.ae/corporate/media-centre/fact-sheets/dubai-airports

FAA investigating drone scare that grounded flights at Newark airport. (2019, January). Columbia Broadcasting System New York. Retrieved January 21, 2021, from https://newyork.cbslocal.com/2019/01/23/faa-investigating-newark-airport-drone-scare/

Federal Aviation Administration. (2014). *National runway safety plan 2015-2017*. Retrieved from https://cfapp.icao.int/tools/RSP_ikit/story_content/external_files/2015_ATO_Safety_National_Runway_Safety_Plan.pdf

Federal Aviation Administration. (2018a, July 5). *Fact sheet—Runway safety*. Retrieved from https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=14895

Federal Aviation Administration. (2018b). *National plan of integrated airport systems (NPIAS) 2019–2023*. Retrieved from https://www.faa.gov/airports/planning_capacity/npias/reports/media/NPIAS-Report-2019-2023-Narrative.pdf

Federal Aviation Administration. (2020a). *UAS sightings report* [Data set]. Retrieved from https://www.faa.gov/uas/resources/public_records/uas_sightings_report/

Federal Aviation Administration. (2020b, July 27). *Fact sheet—The Federal Aviation Administration's (FAA) wildlife hazard mitigation program*. Retrieved from https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=14393

Federal Aviation Administration. (2020c). *FAA wildlife strike database* [Data set]. Retrieved from https://wildlife.faa.gov/home

Federal Aviation Administration. (2020d, September 17). *Report a strike report*. Retrieved from https://wildlife.faa.gov/add

Federal Aviation Administration. (2020e, June 3). *Runway incursion mitigation (RIM) program*. Retrieved from https://www.faa.gov/airports/special_programs/rim/

Federal Aviation Administration. (2020f). *FAA runway safety office—Runway incursions (RWS)* [Data set]. Retrieved from https://www.asias.faa.gov/apex/f?p=100:28::::::

Federal Aviation Administration. (2020g, August 18). *Runway incursion*. Retrieved from https://www.faa.gov/airports/runway_safety/resources/runway_incursions/

Federal Aviation Administration. (2020h). *Runway incursion mitigation fiscal year 2019 annual summary report*. Retrieved from https://www.airporttech.tc.faa.gov/Products/Airport-Safety-Papers-Publications/Airport-Safety-Detail/ArtMID/3682/ArticleID/2837/Runway-Incursion-Mitigation-Fiscal-Year-2019-Annual-Summary-Rep

Forrest, A. (2019, April 28). Gatwick drone sighting: Three planes diverted after reports of flying device near airport. *Independent*. Retrieved from https://www.independent.co.uk/news/uk/home-news/gatwick-airport-drone-flights-diverted-easyjet-british-airways-stansted-a8890346.html

Fraport. (2020). *Annual report 2019*. Retrieved from https://www.annualreports.com/HostedData/AnnualReports/PDF/OTC_FPRUY_2019.pdf

GardaWorld. (2019, March 22). *Germany: Drone briefly suspends flight operations at Frankfurt airport March 22/update 1*. Retrieved from https://www.garda.com/crisis24/news-alerts/215271/germany-drone-briefly-suspends-flight-operations-at-frankfurt-airport-march-22-update-1

Gettinger, D., & Michel, A. H. (2015). *Drone sightings and close encounters: An analysis*. Bard College, Center for the Study of the Drone. Retrieved from https://dronecenter.bard.edu/files/2015/12/12-11-Drone-Sightings-and-Close-Encounters.pdf

Gudsell, K. (2018, November 12). *Drone disrupting airspace "could have been catastrophic"*. RNZ. Retrieved from https://www.rnz.co.nz/news/national/375686/drone-disrupting-airspace-could-have-been-catastrophic

GulfInsider. (2019, December 26). *Drones disrupt flight operations at Muscat international airport*. Retrieved from https://www.gulf-insider.com/drones-disrupt-flight-operations-at-muscat-international-airport/

Heathrow Airport Limited. (2020). *Monthly traffic statistics up to August 2020, excluding Gatwick, Stansted, Edinburgh, Naples, Aberdeen, Glasgow and Southampton* [Data set]. Retrieved from https://www.heathrow.com/company/investor-centre/reports/traffic-statistics

Hollan, M. (2020, March 2). *Frankfurt airport temporarily shut down after drone sighting*. Fox News. Retrieved from https://www.foxnews.com/travel/frankfurt-airport-shut-down-drone-sighting

Ivy Holdco Limited. (2020). *Annual report and the consolidated and parent company financial statements for the 9 month period ended 31 December 2019*. Retrieved from https://www.gatwickairport.com/globalassets/business--community/investors/april-2020/ivy-holdco-limited-consolidated-financial-statements-31-december-2019.pdf.

Johnson, M. E., Zhao, X., Faulkner, B., & Young, J. P. (2016). Statistical models of runway incursions based on runway intersections and taxiways. *Journal of Aviation Technology and Engineering*, *5*(2), Article 3. https://doi.org/10.7771/2159-6670.1121

Lomas, N. (2019, May 9). *Drone sighting at Germany's busiest airport grounds flights for about an hour*. TechCrunch. Retrieved from https://techcrunch.com/2019/05/09/drone-sighting-at-germanys-busiest-airport-grounds-flights-for-about-an-hour/

Martin, G. (2019, January 8). *London's Heathrow airport briefly closed following possible drone sighting*. Forbes. Retrieved from https://www.forbes.com/sites/grantmartin/2019/01/08/londons-heathrow-airport-briefly-closed-following-possible-drone-sighting/#45694ae33158

Mathew, J. K., Major, W. L., Hubbard, S. M., & Bullock, D. M. (2017). Statistical modelling of runway incursion occurences in the United States. *Journal of Air Transport Management*, *65*, 54–62. https://doi.org/10.1016/j.jairtraman.2017.09.003

Muscat International Airport. (2019, January 6). *Muscat International competes for world's best airport title*. Retrieved from https://www.muscatairport.co.om/en/news/muscat-international-competes-for-worlds-best-airport-title

Reuters. (2019, September 22). *Two flights diverted from Dubai due to suspected drones*. Retrieved from https://www.reuters.com/article/us-emirates-security-airport/two-flights-diverted-from-dubai-due-to-suspected-drones-idUSKBN1W70GM

Sharjah Airport. (n.d.). *Airport statistics*. Retrieved from https://www.sharjahairport.ae/en/business/media-center/airport-statistics/?statistics-for-year-2019

Shepardson, D. (2019, January 23). *FAA details impact of drone sightings on Newark airport*. Reuters. Retrieved from https://www.reuters.com/article/us-usa-drones/faa-details-impact-of-drone-sightings-on-newark-airport-idUSKCN1PH243

Shurafa, S. A. (2019, November 28). *Flights diverted from Sharjah International Airport due to suspected drone incident*. Gulf News. Retrieved from https://gulfnews.com/uae/flights-diverted-from-sharjah-international-airport-due-to-suspected-drone-incident-1.1574924509818

Silk, R. (2019, January 31). As drones proliferate, U.S. aviation in holding pattern. *Travel Weekly*. Retrieved January 21, 2021, from https://www.travelweekly.com/Travel-News/Airline-News/As-drones-proliferate-aviation-in-holding-pattern

SKYbrary. (2020, February 25). *Bird behaviour*. Retrieved from https://www.skybrary.aero/index.php/Bird_Behaviour#Bird_Flight_Habits

The Port Authority of NY & NJ. (2020). *2019 airport traffic report*. Retrieved from https://corpinfo.panynj.gov/documents/2019/

Unmanned Aircraft Safety Team. (2017). *Drone sightings analysis and recommendations*. Retrieved from https://www.unmannedaircraftsafetyteam.org/wp-content/uploads/2018/01/UAST-Sightings-Executive-Summary-2017.pdf

Wang, C., & Hubbard, S. M. (2021). Characteristics of unmanned aircraft systems (UAS) sightings and airport safety. *Journal of Aviation Technology and Engineering*, *10*(2), 16–33. https://doi.org/10.7771/2159-6670.1238

Wang, C., & Hubbard, S. M. (2022). Unmanned aircraft systems (UAS) sighting data 2016 to 2019 [Data set]. *Purdue University Research Repository*. doi: https://doi.org/10.4231/H31Y-7197

Wellington Airport. (2019). *Wellington Airport annual review 2018*. Retrieved from https://www.wellingtonairport.co.nz/business/investor-services/annual-reviews/

Wilke, S., Majumdar, A., & Ochieng, W. Y. (2015). Modelling runway incursion severity. *Accident Analysis & Prevention*, *79*, 88–99. https://doi.org/10.1016/j.aap.2015.03.016

Wolgelenter, M. (2019, February 15). Flights at Dubai airport halted over "drone activity". *The New York Times*. Retrieved from https://www.nytimes.com/2019/02/15/world/middleeast/dubai-airport-drone.html

Yeginsu, C. (2018, December 24). 1 broken drone, no video, 2 suspects released: Gatwick episode doesn't add up. *The New York Times*. Retrieved from https://www.nytimes.com/2018/12/24/world/europe/gatwick-airport-drone.html

Yu, E. (2019, June 19). *Singapore Changi airport shuts runway over drone sighting*. ZDNet. Retrieved from https://www.zdnet.com/article/singapore-changi-airport-shuts-runway-over-drone-sighting/