Monitoring Risk Associated with Operations of Unmanned Aircraft Systems (UAS) in the National Airspace System: Models for Analysis of Mandatory Occurrence Reports involving UAS-Manned Aircraft Encounters

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Unmanned aircraft systems (UAS) are operating in the national airspace (NAS) in increasing numbers, and at times have flown in close proximity to manned aircraft. These events are reported in part in Federal Aviation Administration (FAA) Mandatory Occurrence Report (MOR) data. The Volpe Center has developed two models to monitor risk associated with UAS-manned aircraft encounters in MOR data. First, a severity categorization model provides a snapshot of the risk of UAS-manned aircraft encounters in MOR data, in terms of reported proximity between aircraft and proximity of the event to the closest airport. Second, a severity quantification model estimates the probability of collision and probability of fatality given collision inherent in the physical parameters of the encounter. Outputs of the model distinguish serious events from less serious events and 'non-events'; and can be tracked over time to assess the effects of technology, industry, and policy changes with respect to UAS integration. In all, results show most MORs are less serious or 'non-events' while a limited number of MORs carry increased risk, merit further analysis, and provide cause for improved data collection.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
oz	ounces	28.35	grams	g
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd
km	kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
mL	milliliters	0.034	fluid ounces	fl oz
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
g	grams	0.035	ounces	oz
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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Acronyms and Abbreviations

ALR	Acceptable Level of Risk
ATC	Air Traffic Control
ATO	Air Traffic Organization
FAA	Federal Aviation Administration
FT or ft	Feet
MOR	Mandatory Occurrence Report
NAS	National Airspace System
NMAC	Near Mid-Air Collision
Lbs.	Pounds
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle

Preface

This report was prepared by the Transportation Human Factors Division of the Safety Management and Human Factors Technical Center and the Air Navigation & Surveillance Division of the Air Traffic Systems and Operations Technical Center at the U.S. Department of Transportation, John A. Volpe National Transportation Systems Center. It was completed with funding from the Federal Aviation Administration (FAA) Emerging Technologies Office (AJV-0). Thank you to Alan Yost and Emma Ranalli for assistance with the qualitative analysis. Thank you to Britt McNeill, Gerry Pilj, Firdu Bati, and Pradip Som for discussions on the models.

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Executive Summary

Risk in the National Airspace System (NAS) is a function of the probability of an event and the severity of the consequences of that event. Any discussion of issues of risk involved with the operation of Unmanned Aerial Systems (UAS) in the NAS must include a valid and reliable indication of the severity of the outcome of adverse events associated with UAS operations. Adverse events involving UAS operations are reported by Federal Aviation Administration (FAA) in the form of a Mandatory Occurrence Report (MOR). The events reported in MORs range from possible sightings of a UAS to near collisions with a manned commercial air carriers. Therefore, while some reports describe situations involving little or no risk, others describe Near Mid Air Collisions (NMACs). Because of the wide range of types of events, a method for categorizing the events by severity was needed to be able to quantify the number of serious events from less serious events and 'non-events' (such as potential sightings with no operational impact and duplicate reports). Such analysis could be used to quickly summarize these events and provide an indication of NAS performance.

This paper describes ways to monitor risk in the NAS at different levels of precision. First, the process used to develop and refine a method for categorizing the severity of the outcome of events reported in MORs is discussed. The criteria for factors to be used in the severity categorization model were those that were reliably reported in the MORs and useful in discriminating between the severity of most of the reports. Again, the purpose of the categorization model was to provide a quick, high-level snapshot of NAS performance in terms of risk of UAS operations to manned aircraft operations. Given these criteria, the factors agreed to be used in the severity categorization process were the proximity of the UAS to the manned aircraft and the proximity of the event to an airport.

The paper demonstrates the use of this categorization scheme as applied to 2,048 MORs submitted to the FAA from June 5, 2016 to June 5, 2017. These data are presented in various ways (e.g., summary, by quarter, by airspace) to show possible applications to performance monitoring. Finally, we describe the development of a quantitative model to numerically determine the probability of collision and the probability of a fatality given a collision inherent in the physical parameters of the MOR. This model could be used to monitor NAS performance and assess the effects of changes in the system in a more detailed and targeted fashion. Probability of collision and probability of fatality given a collision are calculated on a per-manned-aircraft (or per Air Traffic Control) operation basis, in order to compare to baseline values established in the FAA Air Traffic Organization (ATO) safety standards in the same units.

Probability of collision takes into account the density of manned aircraft operations, the number of MORs, the number of NMAC reported and the traditional proximity criteria for a NMAC. Probability of fatality given a collision takes into account the type of manned aircraft and was calculated based on assumptions of the: mass of the UAS, speed of manned aircraft, and the likelihood of critical structural damage to the manned aircraft. Results are also analyzed with the Acceptable Level of Risk (ALR) approach to determine if a collective risk threshold criteria was met. Finally, the paper contains recommendation for refinement of MOR data collection and for continued performance monitoring of risk in the NAS.

Introduction

Risk in the National Airspace System (NAS) is a function of the probability of an event and the severity of the consequences of that event. Any discussion of issues of risk involved with the operation of Unmanned Aerial Systems (UAS) in the NAS must include a valid and reliable indication of the severity of the outcome of adverse events associated with UAS operations. Adverse events involving UAS operations are reported by Federal Aviation Administration (FAA) in the form of a Mandatory Occurrence Report (MOR). The events reported in MORs range from possible sightings of a UAS to near collisions with a manned commercial air carriers. Therefore, while some reports describe situations involving little or no risk, others describe high-risk Near Mid Air Collisions (NMACs). Because of the wide range of types of events, a method for categorizing the events by severity was needed to be able to quantify the number of serious events from less serious events and 'non-events' (such as potential sightings with no operational impact and duplicate reports). Such an analysis could be used to quickly summarize these events and provide an indication of NAS performance.

This paper describes ways to monitor risk in the NAS at different levels of precision. First, the process used to develop and refine a method for categorizing the severity of the outcome of events reported in MORs is discussed. The paper then demonstrates the categories with one year of MOR data presented in summary and as applied on a quarterly basis. The latter exemplifies how the model could be used to quickly summarize the data in real time. Finally, we describe the development of a quantitative model to more precisely determine the probability of collision and the probability of a fatality given a collision. This model could be used to monitor NAS performance and assess the effects of changes in the system in a more detailed and targeted fashion.

Severity Categorization Model

Model Development

The process used to categorize the severity of MORs involving UAS operations was similar to that used by Volpe to develop a method of categorizing the severity of the outcome of runway incursions to assess risk in surface operations (Cardosi, Hannon, Sheridan, & Davis, 2005). For both runway incursions and MORs, a pre-requisite for the categorization scheme was that the information used to classify severity must be reliably available in the FAA reports. That is, any information that was deemed relevant (or even important) that was *not* reliably reported was not included as a final factor.

Identification of Critical Factors

The first step in the development of a severity categorization scheme was to identify the foundational critical factors and their relative importance. The proposed factors and their weightings were drafted by Subject Matter Experts at the Volpe Center and then discussed with FAA's Performance and Analytics Team (AJI-333) personnel. As a result of these discussions, refinements were made. The resulting model categorizes each MOR involving UAS into a relative severity category. As with the runway incursion severity categorization scheme (Cardosi et al., 2005), the foundation for the severity categorization of MORs was the estimated proximity between the manned aircraft and the UAS. This distance is usually estimated by the pilot of the manned aircraft who reports the distance to Air Traffic Control (ATC). It can, however, also be estimated by a tower controller who observes an encounter.

The categorization scheme, as originally proposed, contained nine mutually exclusive categories (see Table 1); they are presented here as documentation of the factors considered in the development of the model and as a proposal for operational categories that would be useful to monitor over time. The first three categories (i.e., A, B, C) in this severity scheme categorized conflicts between UAS and manned aircraft. The most severe category in the preliminary categorization scheme was mid-air collisions. At the time, no such events existed in the MOR database, but it was clear that the category would be desirable for a data base of future events. The next level of severity (category B) were events identified as having "significant potential for collision". This category included events classified by FAA Flight Standards as final NMACs, events in which there was less than 500 feet (ft) reported between a manned aircraft and UAS, events in which the manned aircraft took evasive action to avoid a collision, and events described as 'close calls' in which the pilot of the manned aircraft did not detect the UAS in time to maneuver. The third category (category C) consisted of descriptions of UAS activity within 3 miles but more than 500 feet from manned aircraft. The fourth severity category (category D) contained reports of UAS activity that did not indicate a conflict with a manned aircraft—these reports either did not include proximity information, or specified a distance of more than 3 miles between the manned aircraft and UAS. This category was subdivided by characterization of potential risk as indicated by the distance of the UAS operation to an airport. The logic behind this category was that UAS operations within five miles of an airport present higher risk, compared to operations greater than five miles from an airport, since at the time of the MORs, activity within 5 miles of an airport required notification of the FAA. This meant that the operator was either ignorant or in defiance of the rule. Similarly, events within one mile of an airport were deemed more serious because of the increased probability of encountering a manned aircraft in a critical phase of flight (i.e., takeoff or landing). The remaining categories (F-I) were those that had no relation to risk to manned aircraft, but could be of interest (such as those relating to privacy issues or UAS operations near hazards).

Table 1. Categories considered in initial analysis, with descriptions.

INITIAL CATEGORY	DESCRIPTION
A	Mid-air collision between manned aircraft and UAV
B	Significant potential for collision (1) 'Final' (i.e., verified by FAA Flight Standards) NMAC (2) closest proximity of less than 500 ft (3) corrective/evasive action was taken to avoid a collision (4) 'close call' reported with insufficient time to maneuver
C	UAV activity reported near manned aircraft (more than 500 ft & less than 3 miles)
D	UAV observed with no conflict (1) within one mile from airport

INITIAL CATEGORY	DESCRIPTION
	(2) greater than one mile but less than five miles from airport (3) greater than five miles from airport (4) distance from airport unknown
E	Possible UAV sighting (reporter unsure)
F	Unnecessary report; Notification of UAV activity known to ATC
G	UAV malfunction (e.g., UAV emergencies/lost link/lost comm)
H	Other UAV report (1) UAV operating in restricted airspace (2) Privacy/noise/citizen concern (3) UAV reported near a hazard (e.g., firefighting)
I	Not a valid MOR (e.g., duplicate report, test report)

Refinement of Critical Factors

After the first round of discussions of the model development with FAA, it was determined that potential risk to manned aircraft should be the focus of the severity scheme; therefore, only categories A through D of Table 1 would be used. Categories E through I would not be used in the analysis. Reports in Category F and I were excluded from the analysis. Reports in Categories E, G, and H were redistributed into categories based on their proximity to manned aircraft, with the majority considered sightings with no conflict.

After simplifying the categorization scheme to focus on closest proximity and considering additional factors which were both relevant and available, the list of critical factors to be considered, in addition to the closest proximity, was refined to the following:

- *Size of UAS (large/small).* An event involving a large UAS would be considered more severe than an event involving a small UAS. A large UAS was defined as either over 55 pounds (lbs.) or described as "large" in the MOR narrative.
- *Category of manned aircraft (large/small/rotorcraft).* Events involving rotorcraft would be considered more serious than those involving fixed-wing aircraft (since they are considered more vulnerable given a collision). Within fixed-wing aircraft, events involving smaller aircraft would be considered more severe than those involving larger, more resilient aircraft.
- *Phase of flight of manned aircraft (landing or taking off/other).* Since aircraft are more vulnerable in the takeoff and landing phases of flight than in cruise, any event involving aircraft in either of these critical phases of flights would be classified as more serious than one involving an aircraft at altitude in level flight.
- *Proximity of UAS operation to airport.* UAS operations in close proximity to an airport would be considered higher risk than those greater than five miles from an airport. Furthermore, UAS operations within one mile of an airport would be considered higher risk than those greater than one mile from an airport.
- *Did manned aircraft make an evasive maneuver?* An event with any given closest proximity would be deemed more severe if the aircraft had made an avoidance maneuver than if the same

proximity had occurred by chance, since without the avoidance maneuver, the manned aircraft would have come even closer (if not impacted) the UAS. For example, if an aircraft made an avoidance maneuver to increase the distance between it and the UAS and still came within 100 ft of the UAS, this would be considered a more severe event than if the manned aircraft came within 100 ft of the UAS without any avoidance maneuver.

Preliminary Assessment of Factors

Volpe analyzed MORs submitted over six months (N=944, note this excludes invalid, duplicate and unnecessary [authorized] reports) for the following factors: closest proximity between UAS and manned aircraft, size of UAS, category of manned aircraft, phase of flight of manned aircraft, proximity to airport, and whether or not the manned aircraft made an avoidance maneuver. The results were enlightening in terms of what factors would be useful to include in a categorization model. The reports routinely contained an estimated closest proximity and type of manned aircraft. While a critical phase of flight (taking off or landing) was occasionally reported, the proximity to an airport was more reliably reported. These two factors are not mutually exclusive—aircraft operating in close proximity to an airport at a low altitude are likely in a landing or takeoff phase of flight. More importantly UAS operations in proximity to an airport presents risk in the NAS that is proportional to the proximity to the airport. For these reasons, proximity to the airport was selected as the critical factor to be included in the severity scheme in addition to the closest proximity reported in conflicts with manned aircraft.

Several factors were rarely reported. For example, of the 944 reports analyzed, only 24 reports specified that the UAS was large. Only 40 of the 944 reports contained a description of an avoidance maneuver by the manned aircraft. (Note that none of the reports described a UAS making an avoidance maneuver.) Since these factors were so rarely reported, they were not deemed useful in a broad severity categorization scheme. Furthermore, in subsequent discussion, FAA (AJI-333) argued that an event that included the manned aircraft making an avoidance maneuver should *not* be regarded as a higher severity than one that did not and resulted in the same closest proximity, all other factors being equal.

While it would be ideal to include a metric considering *both* vertical and horizontal proximity, only 11% of the MORs contained estimates of both dimensions. Because of this, when only a single dimension (was vertical, horizontal, or unreported) is reported in the MORs, it is included in categorization model as the closest. Where both dimensions are reported, the MOR is categorized based on the dimension with greatest separation, e.g. a UAS described as 100 feet above and 500 feet to the left of a manned aircraft is categorized according to the 500 foot horizontal separation.

Resolution of Critical Factors

The criteria for factors to be used in the severity categorization model were those that were reliably reported in the MORs and useful in discriminating between the severity of most of the reports. Again, the purpose of the categorization model was to provide a quick, high-level snapshot of NAS performance. Given these criteria, the factors agreed to be used in the severity categorization process were the **proximity of the UAS to the manned aircraft** and the **proximity of the event to an airport**. This scheme would allow for a quick initial screening of the MORs with respect to severity utilizing information likely to be reported without the need for further investigation. The proposed categorization scheme (with factors and their weightings) is shown in Figure 1.

Collisions were not included in this scheme and would be counted separately in performance monitoring. Our original scheme used 500 feet as significant potential for collision. However, we learned that FAA was considering using 100' feet as the criterion for a NMAC with a UAS, so we added a category for less than 100 feet or NMAC. We also learned that FAA has proposed using 2000 feet in other classifications (in the definition of well-clear) so we used that as the cut-off for events which have the potential for conflict. Finally, we distinguished between events which report a well-clear proximity and events which do not report a proximity at all (D vs. E).

Proximity to Manned Aircraft	Airport Proximity: Less than 1 mile from airport	Airport Proximity: Greater than 1 but less than 5 miles of an airport	Airport Proximity: Greater than 5 miles from an airport or unreported
A: Collision narrowly avoided *Final NMAC or ≤100ft proximity*	A1	A2	A3
B: Significant collision potential *≤500 ft proximity*	B1	B2	B3
C: Potential conflict *≤2000 ft proximity*	C1	C2	C3
D: Sighting only *Well clear, >2000 ft proximity*	D1	D2	D3
E: Sighting only *No proximity reported*	E1	E2	E3

Figure 1. Severity Classification Based on Proximity to Manned Aircraft and Airport.

Output of Severity Categorization Model

This categorization scheme was applied to MORs submitted between June 5, 2016 and June 5, 2017 (total of 2,048 MORs); the results are shown in the figures below. Figure 2 shows summary data for the entire year. Of the 2,048 MORs during this timeframe, 1,957 MORs were applicable for analysis; 24 MORs were unnecessary notifications of permitted UAS activity to ATC, and 67 MORS were not valid (i.e., a duplicate report or a "test" report).

Proximity to Manned Aircraft	Less than 1 mile from airport	Greater than 1 but less than 5 miles from an airport	Greater than 5 miles or unreported	*TOTAL*
A: Collision narrowly avoided *Final NMAC or ≤100ft proximity*	73	179	235	487
B: Significant collision potential *≤500 ft proximity*	55	159	263	477
C: Potential conflict *≤2000 ft proximity*	15	68	113	196
D: Sighting only *Well clear, >2000 ft proximity*	10	25	50	85
E: Sighting only *No proximity reported*	133	221	358	712
TOTAL	286	652	1019	1957

Figure 2. Severity Classification for June 5, 2016 to June 5, 2017.

Figure 3 shows the same data categorized as a "major" (red), "minor" (orange), "minimal" (yellow) event, or "non-event" (green). It is important to note that these categories are arbitrary and could be refined based on different operational assumptions (e.g., as to what constitutes major and minor risk).

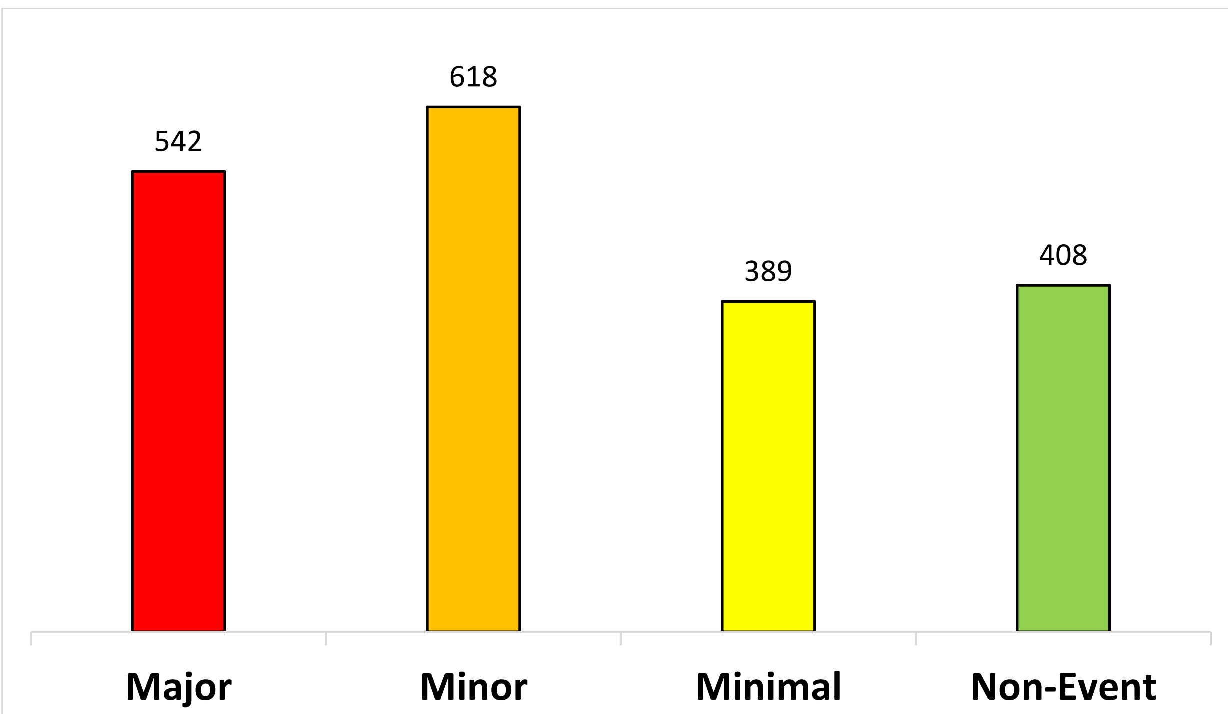


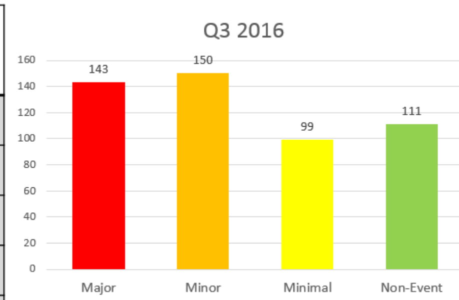
Figure 3. The total number of MORs by color-coded severity category.

Figures 4-7 present an in-depth look at the MOR data by quarter, beginning in 2016 Quarter 3 and ending in 2017 Quarter 2. Data presented in this manner can be used to quickly assess changes in the NAS during a given timeframe.

Airport Proximity

Proximity to Manned Aircraft

	Less than 1 mile from airport	Greater than 1 but less than 5 miles from an airport	Greater than 5 miles or unreported	*TOTAL*
A: Collision narrowly avoided *Final NMAC or ≤100ft proximity*	25	43	59	127
B: Significant collision potential *≤500 ft proximity*	16	35	59	110
C: Potential conflict *≤2000 ft proximity*	5	23	28	56
D: Sighting only *Well clear, >2000 ft proximity*	4	8	14	26
E: Sighting only *No proximity reported*	34	53	97	184
TOTAL	84	162	257	503



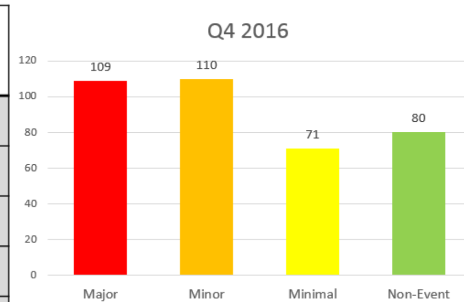
Red-Major	Orange-Minor	Yellow-Minimal	Green-Non-event	Total
143	150	99	111	503

Figure 4. Severity Classification for July through September 2016.

Airport Proximity

Proximity to Manned Aircraft

	Less than 1 mile from airport	Greater than 1 but less than 5 miles from an airport	Greater than 5 miles or unreported	*TOTAL*
A: Collision narrowly avoided *Final NMAC or ≤100ft proximity*	11	39	43	93
B: Significant collision potential *≤500 ft proximity*	16	28	46	90
C: Potential conflict *≤2000 ft proximity*	5	14	17	36
D: Sighting only *Well clear, >2000 ft proximity*	1	1	10	12
E: Sighting only *No proximity reported*	29	40	70	139
TOTAL	62	122	186	370



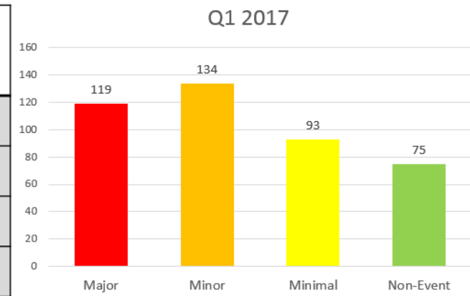
Red-Major	Orange-Minor	Yellow-Minimal	Green-Non-event	Total
109	110	71	80	370

Figure 5. Severity Classification for October through December 2016.

Airport Proximity

Proximity to Manned Aircraft

	Less than 1 mile from airport	Greater than 1 but less than 5 miles from an airport	Greater than 5 miles or unreported	*TOTAL*
A: Collision narrowly avoided *Final NMAC or ≤100ft proximity*	18	38	54	110
B: Significant collision potential *≤500 ft proximity*	9	41	61	111
C: Potential conflict *≤2000 ft proximity*	2	6	24	32
D: Sighting only *Well clear, >2000 ft proximity*	1	7	8	16
E: Sighting only *No proximity reported*	31	54	67	152
TOTAL	61	146	214	421



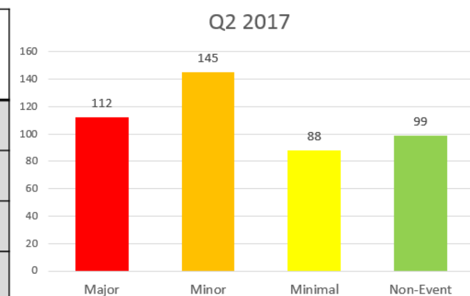
Red-Major	Orange-Minor	Yellow-Minimal	Green-Non-event	Total
119	134	93	75	421

Figure 6. Severity Classification for January to March 2017.

Airport Proximity

Proximity to Manned Aircraft

	Less than 1 mile from airport	Greater than 1 but less than 5 miles from an airport	Greater than 5 miles or unreported	*TOTAL*
A: Collision narrowly avoided *Final NMAC or ≤100ft proximity*	9	41	51	101
B: Significant collision potential *≤500 ft proximity*	11	31	66	109
C: Potential conflict *≤2000 ft proximity*	3	18	27	48
D: Sighting only *Well clear, >2000 ft proximity*	1	6	15	22
E: Sighting only *No proximity reported*	26	55	84	165
TOTAL	50	151	243	444



Red-Major	Orange-Minor	Yellow-Minimal	Green-Non-event	Total
112	145	88	99	444

Figure 7. Severity Classification for April to June 5, 2017. Note, the data for this quarter are incomplete.

Figure 8 shows a snapshot of monthly trends. Note there is a decrease in MORs in November, December, and January, likely reflecting the decrease in UAS operations during the winter.

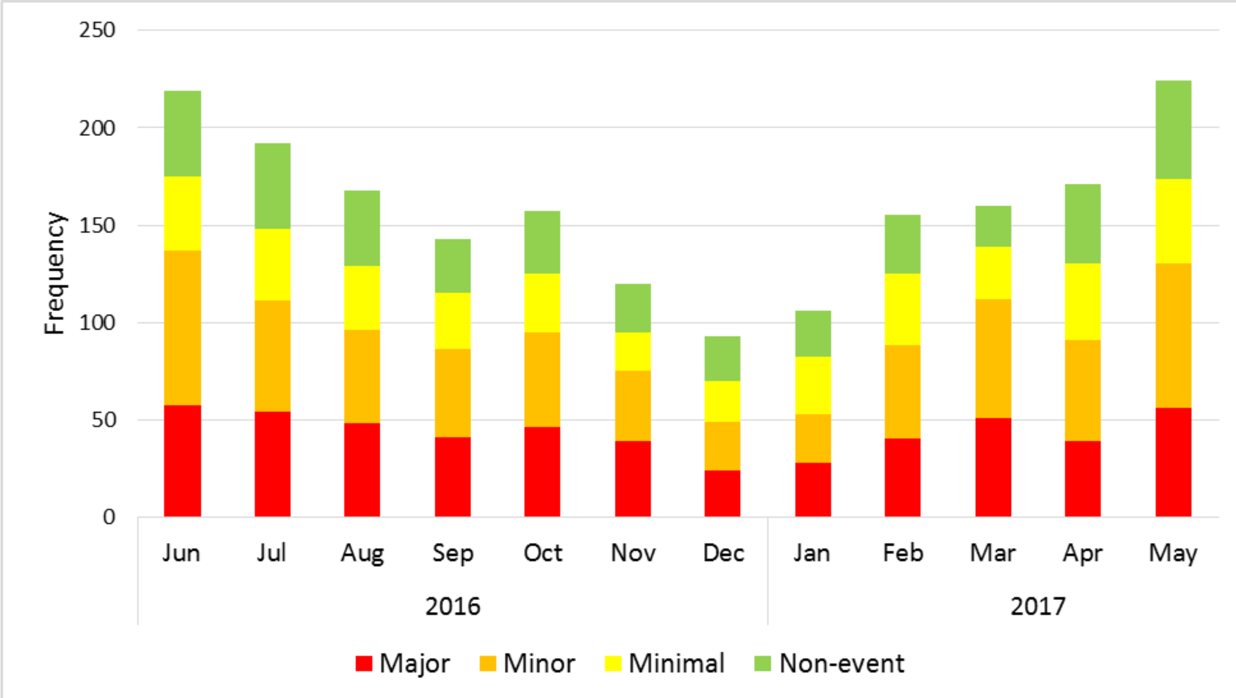


Figure 8. A snap shot of monthly MOR trends.

A detailed analysis of the MORs is necessary to track the frequency of any factors of interest—such as those involving "large UAS", reports of UAS malfunctions, or privacy/noise issues. While these factors are not reliability reported in the majority of the MORs (and thus, were not suitable for the severity metric), the relative frequency of these factors can be examined over time so that they can be analyzed to support needed analysis or to assess effects of a change in the NAS. The frequency of relevant factors of interest, for June 5, 2016-June 5, 2017 in shown in Table 2 by proximity to manned aircraft and in Table 3 by airport proximity.

Table 2. Factors of interest by proximity to manned aircraft.

Manned Aircraft Proximity	All MORs	UAV over 55 lbs.	"Large" UAV	Possible UAV	Maneuver	Intention to Maneuver	UAV malfunction	Restricted airspace	Privacy/ Noise	Near a hazard
A	487	13	15	14	44	11	-	1	-	4
B	477	8	12	21	10	1	-	-	1	2
C	196	5	4	11	4	-	-	-	-	1
D	85	3	4	2	1	-	1	-	-	-
E	712	12	22	54	11	1	24	16	16	14
TOTAL	**1957**	**41**	**57**	**102**	**70**	**13**	**25**	**17**	**17**	**21**

Table 3. Factors of interest by proximity to airport.

Airport Proximity	All MORs	UAV over 55 lbs.	“Large” UAV	Possible UAV	Maneuver	Intention to Maneuver	UAV malfunction	Restricted airspace	Privacy/ Noise	Near a hazard
< 1 mile	286	7	7	9	14	1	-	-	-	1
1-5 miles	652	7	16	22	26	6	2	3	2	1
> 5 miles or unknown	1019	27	34	71	30	6	23	14	15	19
TOTAL	**1957**	**41**	**57**	**102**	**70**	**13**	**25**	**17**	**17**	**21**

Recommendation for Refinement of Data Collection and Continued Performance Monitoring

Analysis of MOR data to support NAS performance monitoring would benefit from the report of additional information and improvements to the consistency with which current data (on the form) are reported. For example, while “proximity” is almost always reported, it would be helpful to know whether this is a vertical or horizontal value (and what the value was in the other dimension, if known). Similarly, an estimate of the altitude of the UAS, and the altitude of the manned aircraft at the time of the encounter are critical information that would benefit from more consistent reporting. Also, since commercial and military UAS operations will become more prevalent, the addition of the following data fields should be considered to help with the analysis of adverse events:

- Characteristics of UAS operation:
- Type of mission:
    - Was a flight plan filed? (Yes/No)
        - If so, was the flight plan followed?
    - Was UAS in communication with ATC at the time of the event?
    - Was the UAS operating in Visual Line of Sight or Beyond Visual Line of Sight?
    - Was there a lost link or other malfunction?

These changes to the MOR data collection form and increased consistency of reporting would help to support the analysis of critical factors identified in Table 1. As the number of UAS operations increase in the NAS, so too will the number of adverse events. Analysis of the causal and contributing factors of these events will be the first step in designing and implementing effective risk-mitigation strategies.

Severity Quantification Model

With the severity categorization model completed, Volpe turned to developing a more sophisticated quantitative model. The original intent for this model was to emulate the model used for runway incursions (Cardosi et al., 2005) which quantified the severity of the event based on the closest proximity between the aircraft and other vehicle (aircraft or ground vehicle). The model then augmented the severity rating that was based on proximity with factors such as the size and speed of the aircraft, the magnitude of avoidance maneuvers, and environmental factors (such as visibility). The direction for model development was changed based on feedback from FAA AJI-333. This feedback indicated that a more useful model would be one which would use data from MORs and other data sources to more precisely determine probability of collision between a manned aircraft and a UAS, and the probability of a fatality given a collision. This quantitative model also uses the concept of 'worst credible outcome' to estimate how severe the situation in an MOR could have been.

Model Development

As stated above, probability of collision [abbreviated "P(Collision)"] and probability of fatality given collision [abbreviated "P(Fatality|Collision)"] are the two critical terms calculated in the quantitative model. Multiplying P(Collision) and P(Fatality|Collision) yields the probability of one or more fatalities occurring [abbreviated "P(Fatality)"], if the encounter were to happen again in the future with the same physical parameters. Very few collisions between UAS and manned aircraft have been observed to date, thus the model provides a metric describing potential for fatalities in the NAS, calculated in a consistent and repeatable way. It is important to note that there is an unknown number of unreported encounters between manned and unmanned aircraft. This means that there is an unknown level of variability in any metric that uses the total number of MORs. It is likely that pilots of manned aircraft are more likely to report encounters that they consider to be serious either by virtue of proximity to their aircraft or the physical location of the encounter (e.g., in an airport traffic pattern).

P(Collision) and P(Fatality|Collision) are calculated on a per-manned-aircraft (or per ATC) operation basis, in order to compare to baseline values established in the FAA Air Traffic Organization (ATO) safety standards (Bati, Smiley, & Walton, 2018), in the same units. Both probabilities have undergone several iterations of refinement as more data became available and feedback was received from the FAA and subject matter experts. An analysis of 2,048 MORs submitted to FAA from June 5, 2016 to June 5, 2017 (spanning 366 days) is presented in the following sections.

Probability of Collision per Manned Aircraft Operation

P(Collision) takes several variables into account. The first is the density of manned aircraft operations. A one-year average of traffic density per day was obtained for all Class B airports and some Class C, D, and

E airports in the NAS from the FAA ATO Operations Network (OPSNET) database[1].

If the MOR occurred at an airport for which traffic density data were available, then the data were input to the model; if the MOR occurred at or near an airport for which no density data were available, then, the average traffic density for airports within that class was used as an input to the model. (Note that additional data which describe manned aircraft traffic density at all airports in the NAS, could be used to refine this term in the model).

The number of MORs that involve the presence of a UAS can be used to estimate UAS operational density by airspace class. The number of near mid-air collisions (NMACs) between UAS and manned aircraft in each airspace class was estimated with the number of "final[2]" NMAC. The third factor that is used to estimate the probability of collision is the manned aircraft frontal area (derived from wingspan indicated by make/model recorded in MOR data). The manned aircraft frontal area represents area of collision, thus the ratio of area of collision to NMAC parameters gives the probability of collision given NMAC. The traditional proximity bounds of 500 feet horizontal and 500 feet vertical were used to define NMAC. These variables are used in the equations below to derive P(Collision). The probability of NMAC given an MOR is estimated by the proportion of NMACs given the number of MORs. Both the total number of MORs describing a UAS operation and the number of NMACs are used estimate future occurrences.

P(Collision) = (Term 1) * (Term 2) * (Term 3):

Term 1 Numerator = Number of MOR per day.

Term 1 Denominator = Number of Manned Aircraft (or ATC) operations per day observed at the airport where the MOR occurred.

Term 1 = (#MOR/day) / (#ATC Operations/day) shown in Table 4.

Table 4. ATC Operations per Day at Selected Airports in FAA OPSNET Data (Average over Calendar Year 2017).

Airport	ATC Operations per day
ADW	145
ATL	2,410
BOS	1,112
BWI	717
CLE	335
MIA	1,133

Term 2 Numerator = Number of "final" NMAC observed.

[1]FAA OPSNET data available online: https://aspm.faa.gov/opsnet/sys/main.asp

[2] The FAA designates an MOR as a "final" NMAC after analysis of (including but not limited to) the MOR narrative, manned aircraft pilot estimate of closest proximity and other feedback, air traffic situational awareness surveillance and automation data, etc.

Term 2 Denominator = Number of MOR observed.

Term 2 = (#MAC/#MOR) in each airspace class shown in Table 5.

Table 5. Number of MOR and Final NMAC Observed.

	Class B Airspace	Class C Airspace	Class D Airspace	Class E Airspace
Final NMAC	47	21	31	39
MOR	629	302	397	281
NMAC/MOR	*$7.47*10^{-2}$*	*$6.95*10^{-2}$*	*$7.81*10^{-2}$*	*$1.39*10^{-1}$*

Term 3 Numerator = Manned aircraft frontal area estimated with make/model and wingspan – this is a representation of the area of potential collision.

Term 3 Denominator = NMAC area assuming 500 ft horizontal separation and 500 ft vertical separation.

Term 3 = (Area of MAC) / (Area of NMAC) ≈ 0.1124w2 / {π*(w/2+Δx)*(h+Δz)}. Figure 9 shows a graphical representation of this term, and Table 6 shows statistics for this term. Each data point in Table 6 represents one manned aircraft make/model in the FAA Manned Aircraft Characteristics Database[3]. The worst credible case A(MAC) / A(NMAC) value of 0.006 was used for all MORs.

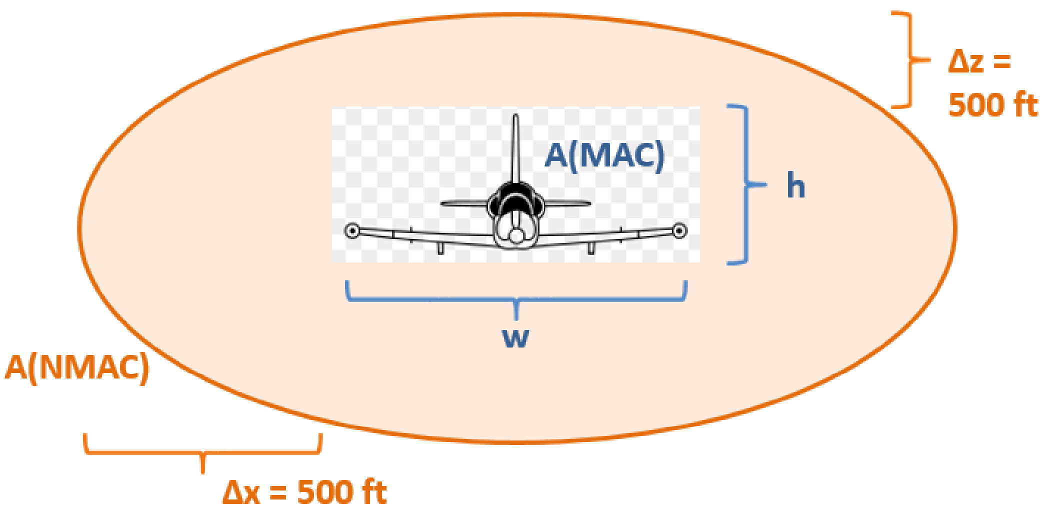
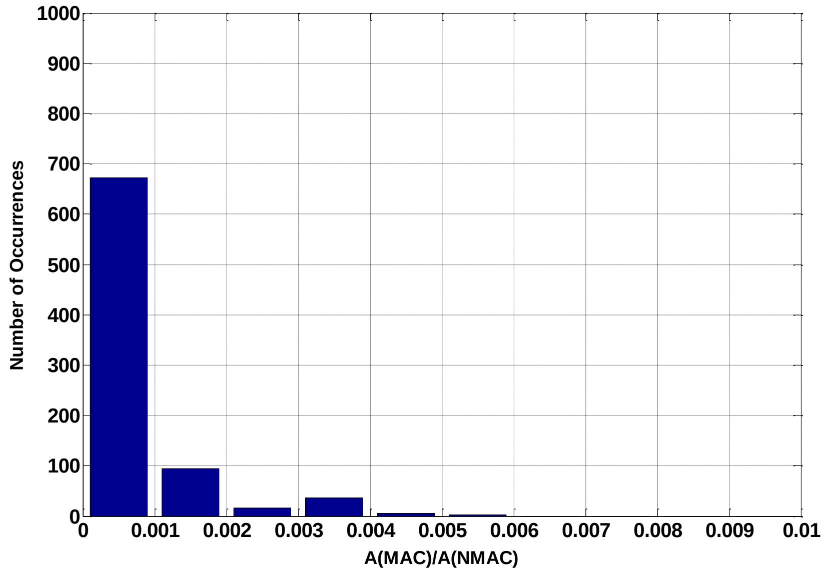


Figure 9. Graphical Representation of Area of Collision A(MAC) and Area of Near Mid-Air Collision A(NMAC).

[3] FAA Manned Aircraft Characteristics Database available online:
https://www.faa.gov/airports/engineering/aircraft_char_database/
Note an earlier version of the database was used to generate Figure 10 and Table 6



A(MAC) / A(NMAC) Statistic	Value
25th Percentile	0.00019
Median	0.00028
75th Percentile	0.00073
95th Percentile	0.0031
Maximum	0.0055

Figure 10. Histogram of A(MAC) Divided by A(NMAC).
Table 6. A(MAC) Divided by A(NMAC) Statistics.

In summary (Term 1) * (Term 2) * (Term 3) =
(#MOR/day) / (#ATC Operations/day) *(#NMAC/#MOR) *(Area of MAC) / (Area of NMAC),
where units within terms with the same color cancel out[4], thus the result has units of MAC/ATC Operation, and can be taken as the expected probability of collision per ATC operation.

Probability of Fatality Given Collision per Manned Aircraft Operation

P(Fatality|Collision) was calculated based on 1) presumed mass of UAS that could collide with the manned aircraft 2) presumed speed of manned aircraft at the time of collision, 3) likelihood of structural damage to the manned aircraft given a collision, and 4) likelihood of that damage occurring at a critical area of the manned aircraft.

Presumed mass of UAS was related to apparent size. MOR data contain a field for the apparent size of the UAS as reported by the manned aircraft pilot. The data typically consist of qualitative descriptions of “small” or “large”; or estimate of largest dimensions such as “1 foot.” If apparent size was qualitatively “small,” then a weighted average of the top 30 registered small UAS masses (Gettinger & Michel, 2017 and various manufacturer data), of approximately 3.5 lbs., was used to compute the probability of a fatality given a collision; if apparent size was qualitatively “large,” then 55 lbs. was used. In the MOR data, the size was rarely identified as “large.”

It was assumed manned aircraft speed is much greater than that of the UAS in a potential collision, thus speed of collision is approximately equal to speed of the manned aircraft, which depends on make/model as well as phase of flight. Manned aircraft speed is abbreviated as “V-operational” for the rest of this section. The FAA Manned Aircraft Characteristics database provides terminal area

[4] The units of Days, #MOR, and Area all cancel out.

operational speeds for many aircraft, which is then used in the following simplistic method to estimate speed at the time of collision:

- If the MOR occurred less than 10 nautical miles away from the nearest airport, and manned aircraft altitude is less than 3,000 feet, then the manned aircraft is assumed to be on short final approach or initial departure; and **V-operational is equal to terminal area speed**
- If manned aircraft altitude is between 3,000 and 10,000 feet, then the manned aircraft is assumed to be in low altitude cruise, initial approach, or is completing departure; and **V-operational is equal to (2*terminal area speed)**
- If the MOR occurred more than 10 nautical miles from the nearest airport, and manned aircraft altitude is greater than 10,000 ft, then the manned aircraft is assumed to be in cruise; and **V-operational is equal to (3*terminal area speed)**

This method of estimating speed of collision could be improved as the FAA database is updated to include cruise speeds of manned aircraft. In addition, more sophisticated aircraft dynamics models can be applied to improve the method. Figure 11 shows V-operational under the current method, each data point represents one MOR where manned aircraft make/model is known and terminal area speed is available. Note that most V-operational values are between 100 and 200 knots, indicating more MORs occur during approach and departure, than during cruise.

The likelihood of structural damage is assumed to be zero below a threshold velocity, and increases above the threshold velocity of impacts. Consider Wilde (2014) where dense metal projectiles weighing up to 9 grams were launched at various speeds at metal plates of various thickness. The impact results in Figure 12 were used to determine a threshold velocity where projectiles of certain size and mass can damage structural elements. The test results relate most closely to dense components of UAS, such as motors or batteries, striking manned aircraft. These components impacting manned aircraft at a critical area, is the worst-case credible risk in the event of a collision.

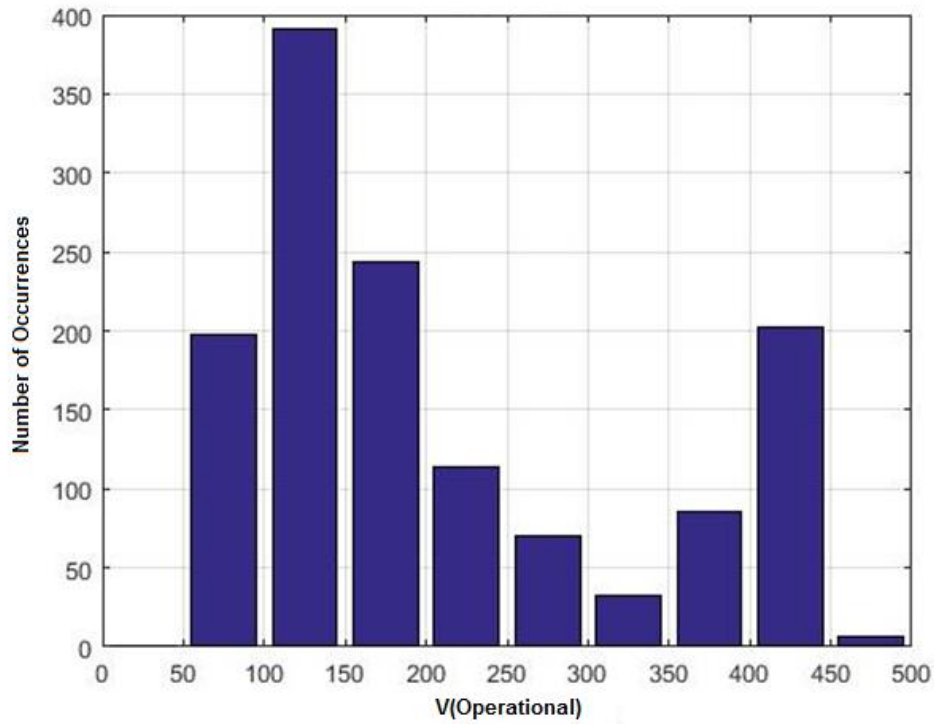


Figure 11. Histogram of Speed of Collision.

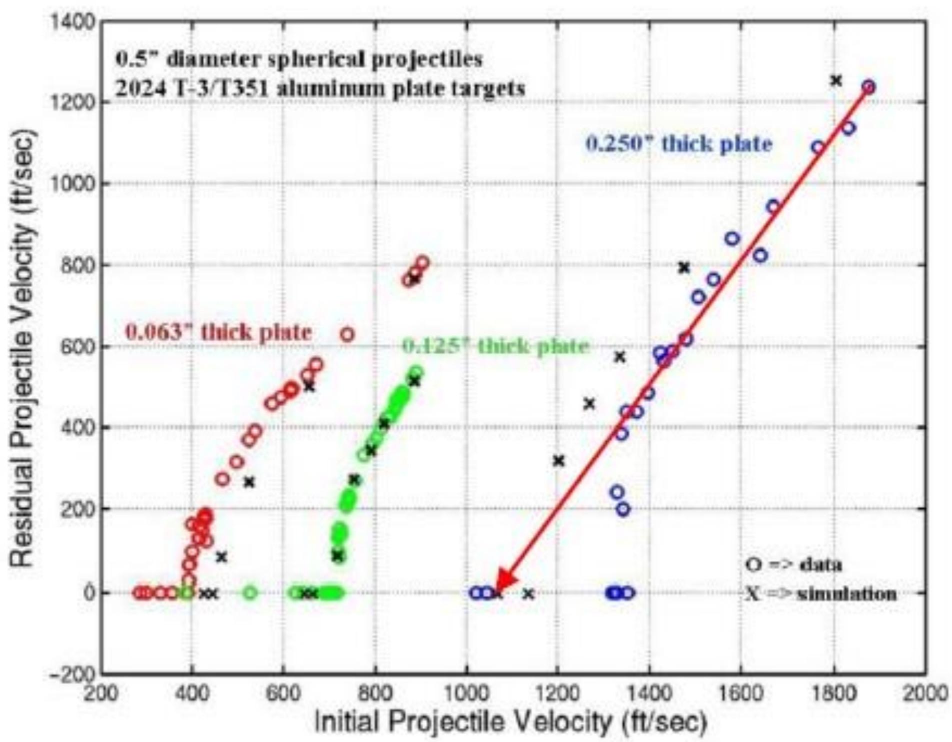


Figure 12. Typical Impact Test Results and Conservative "V50" (Impact Threshold Velocity) Predicted by FAA Penetration Equation (Wilde, 2014).

Impact threshold velocity is referred as "V-threshold" for the rest of this section. V-operational was compared to V-threshold for each MOR, and the following simplistic method was used to determine likelihood of structural damage:

- If V-operational is less than V-threshold, then **likelihood of structural damage is zero**
- If V-operational is greater than V-threshold but less than an upper speed limit, then **likelihood of structural damage increases with linear interpolation for V-operational, between V-threshold and upper speed limit**
    - Upper limit of 700 feet per second (approximately 414 knots) was chosen; this value can be refined in future analyses
    - V-threshold was generally found to be between 200-300 knots
- If V-operational is greater than the upper speed limit, then **likelihood of structural damage is 1.**

Figure 13 shows likelihood of structural damage if a collision occurred with the described physical parameters, for each MOR in the dataset.

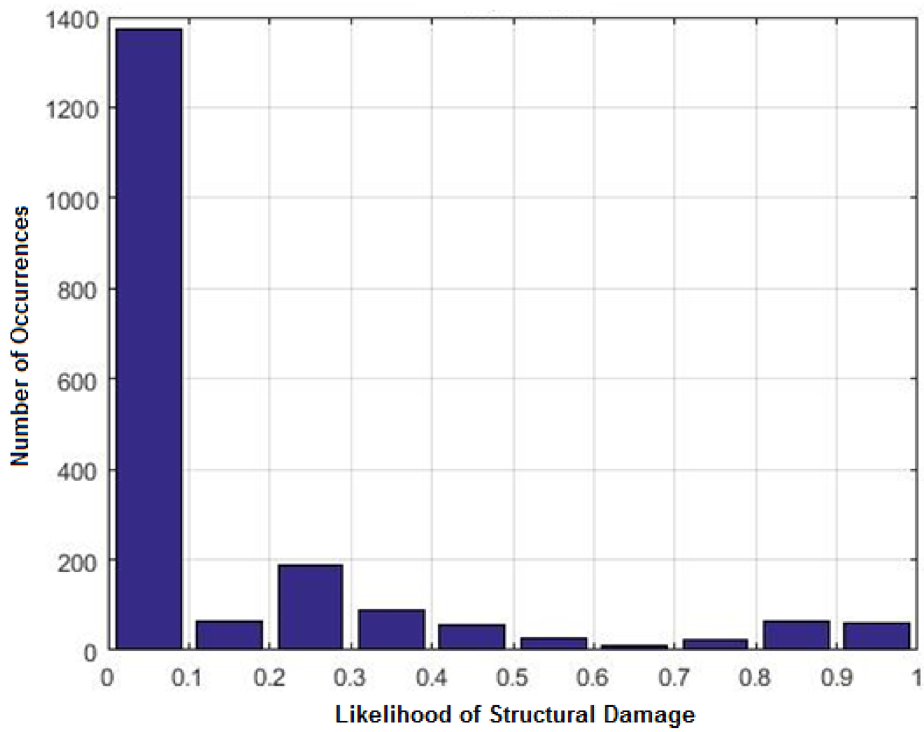


Figure 13. Histogram of Likelihood of Structural Damage.

The final factor in consideration of the probability of a fatality given a collision is the fact that impacts to different areas of the manned aircraft yield different consequences. Olivares et al. (2017) conducted live tests and simulations of UAS (entire aircraft bodies and individual components such as motors) impacting various areas on manned aircraft. The most vulnerable areas include horizontal stabilizers, vertical stabilizers, and windshield. Flaps were somewhat vulnerable, and other areas of the aircraft can safely sustain collisions with 2.7-pound quadcopters and 4-pound fixed-wing small UAS. However, UAS of only these two masses were tested, and only two types of manned aircraft were tested (both business jets). More research is needed to improve empirical data related to UAS-to-manned aircraft collisions. Helicopters, though not tested, were assumed to be more vulnerable than fixed-wing aircraft in general due to the top and back rotors. With the qualitative results from Olivares et al. (2017; shown in Figure 14) and feedback from subject matter experts, a safety mitigation factor was used to estimate likelihood of structural damage occurring at a critical area of the manned aircraft. The following assumptions were used to refine the likelihood of structural damage:

- Helicopters, blimps, and airships – no mitigation, **likelihood of structural damage occurring at critical area = likelihood of structural damage**
- Small fixed-wing manned aircraft, **likelihood of structural damage occurring at critical area = 0.6*likelihood of structural damage**
- Large and heavy fixed-wing manned aircraft, **likelihood of structural damage occurring at critical area = 0.3*likelihood of structural damage.**

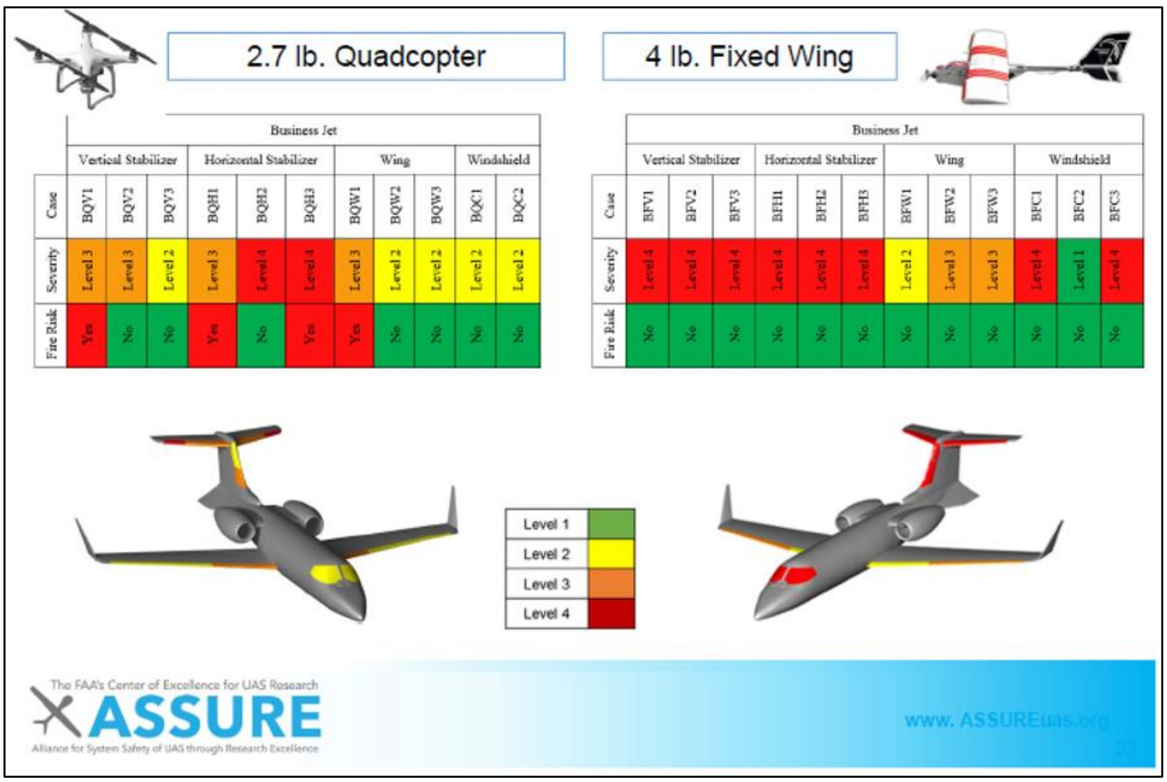


Figure 14. Severity of a sUAS Mid-air Collision with a Business Jet Aircraft (Olivares et al., 2017).

In summary, P(Fatality|Collision) = (Term 4) * (Term 5) where:
Term 4 = Likelihood of structural damage to manned aircraft
Term 5 = Likelihood of structural damage occurring at critical area of manned aircraft

Again the conservative assumption is made that fatalities could occur if the manned aircraft is damaged at a critical area, in event of collision with a small UAS.

Output of Severity Quantification Model

The full equation for P(Fatality) is as follows. Sample outputs for one MOR and for the entire dataset are discussed in this section.

P(Fatality) = P(Collision) * P(Fatality|Collision) =
(Term 1)*(Term 2)*(Term 3)*(Term 4)*(Term 5) =
(#MOR/day) / (#ATC Operations/day) * (#NMAC/#MOR) * (Area of MAC) / (Area of NMAC) * (Likelihood of structural damage to manned aircraft) * (Likelihood of structural damage occurring at critical area of manned aircraft).

Sample Output for One MOR in Miami Class B Airspace

The following MOR was submitted on September 26, 2016, 20:23 UTC, near Miami International Airport:

> While On ILS (approach) for RWY 12 at MIA, Air Carrier reported a UAS near ILS fix VEPCO (5NM NW OF MIA) at 1,700ft. Pilot advised to call facility to provide more information. Pilot spoke to TRACON FLM and stated he saw a black and orange object with 4 (propellers) pass 100ft of his right wing. The object was a hazard to his aircraft and considered this a NMAC. Pilot did not take evasive action, also stated that passengers did see an object out the right side windows. DEN, ROC, MDPD notified.

Quantitative information obtained from the MOR narrative and FAA analysis include:

- Manned aircraft altitude = 1,700 feet
- Distance from airport = 5 nautical miles
- UAS size = small
- Final NMAC = yes
- Airspace class = B
- UAS latitude-longitude = 25.84 degrees N, 80.39 degrees W
- Manned aircraft type = Boeing 767-300[5]

Quantitative terms were calculated as follows:

- Term 1 = (1 MOR observed at MIA on September 26, 2016) / (Average of 1,133 ATC operations at MIA per day) = $8.83*10^{-4}$
- Term 2 = (47 NMAC observed in Class B airspace) / (629 MOR observed in Class B airspace) = $7.47*10^{-2}$
- Term 3 = worst-case A(MAC) / A(NMAC) = $6.00*10^{-3}$
- Term 4 = Likelihood of structural damage to manned aircraft = $3.42*10^{-2}$
- Term 5 = Likelihood of structural damage occurring in critical area of manned aircraft = $3.00*10^{-1}$
- P(Collision) per ATC operation = $3.96*10^{-7}$
- P(Fatality|Collision) = $1.03*10^{-2}$

[5] From FAA manned aircraft characteristics database:
Terminal area speed = 140 knots, wingspan = 156 feet, tail height = 53 feet, maximum takeoff weight = 350,000 pounds (weight class is "heavy")

- P(Fatality) per ATC operation = P(Collision) per ATC operation * P(Fatality|Collision) = 4.06*10^{-9}

With this MOR, the P(Fatality) per ATC operation is calculated to be 4.06*10^{-9}, if the situation described in the Miami MOR example were to occur in the future. The main factor contributing to a non-zero P(Fatality) is that V-operational was slightly higher than V-threshold, resulting in a 3.4% likelihood of structural damage. In all, the l estimate of P(Fatality) is conservative and can be refined in future analyses.

Output for Entire MOR Dataset

P(Fatality) was calculated for 1,336 of 2,048 MORs containing all necessary data elements, and Figure 15 shows the results in log base 10. 763 MORs have P(Fatality) of zero due to likelihood of structural damage (V-threshold < V-operational). Nonzero P(Fatality) values range from 10^{-10} to 10^{-6}. Table 7 shows P(Fatality) summary statistics.

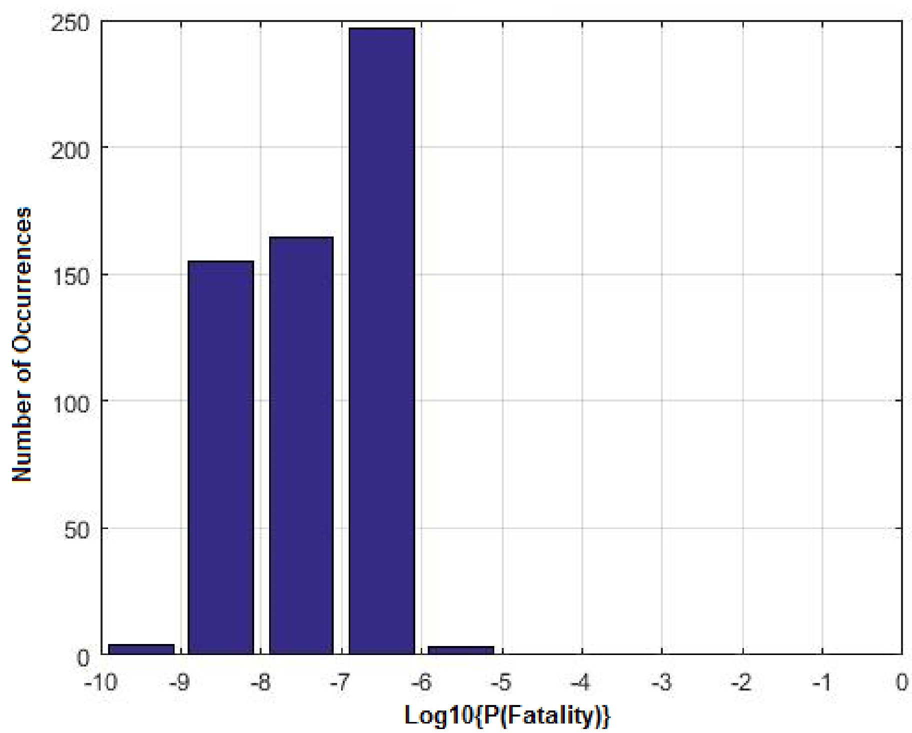


Figure 15. Log10{P(Fatality)} for MORs with All Necessary Data Elements to Complete Calculation.

Table 7. P(Fatality) Summary Statistics.

P(Fatality) Statistic	Value
25th Percentile	0
Median	0
75th Percentile	5.58*10^{-8}
95th Percentile	3.61*10^{-7}
Maximum	1.26*10^{-6}

As with the Severity Categorization Model, the anticipated use of these statistics is to track performance over time and assess the effects of changes in the NAS. Figure 16 shows a snapshot of monthly trends for P(Fatality). The top box-and-whiskers plot shows logarithm base 10 of P(Fatality) for only those MORs with P(Fatality) greater than zero, each month. The middle line represents median, the upper and lower boundaries of the box represent 25th and 75th percentiles, and the whiskers represent 95th percentile. Outliers are plotted with (+) symbols. The bottom bar chart shows number of MOR per month independent of P(Fatality). Note, for example, that December 2016 had the smallest sample size, but had the highest median P(Fatality) for MORs with nonzero P(Fatality). Risk can only be assessed through analysis, not the sheer number of MORs involving UAS operations.

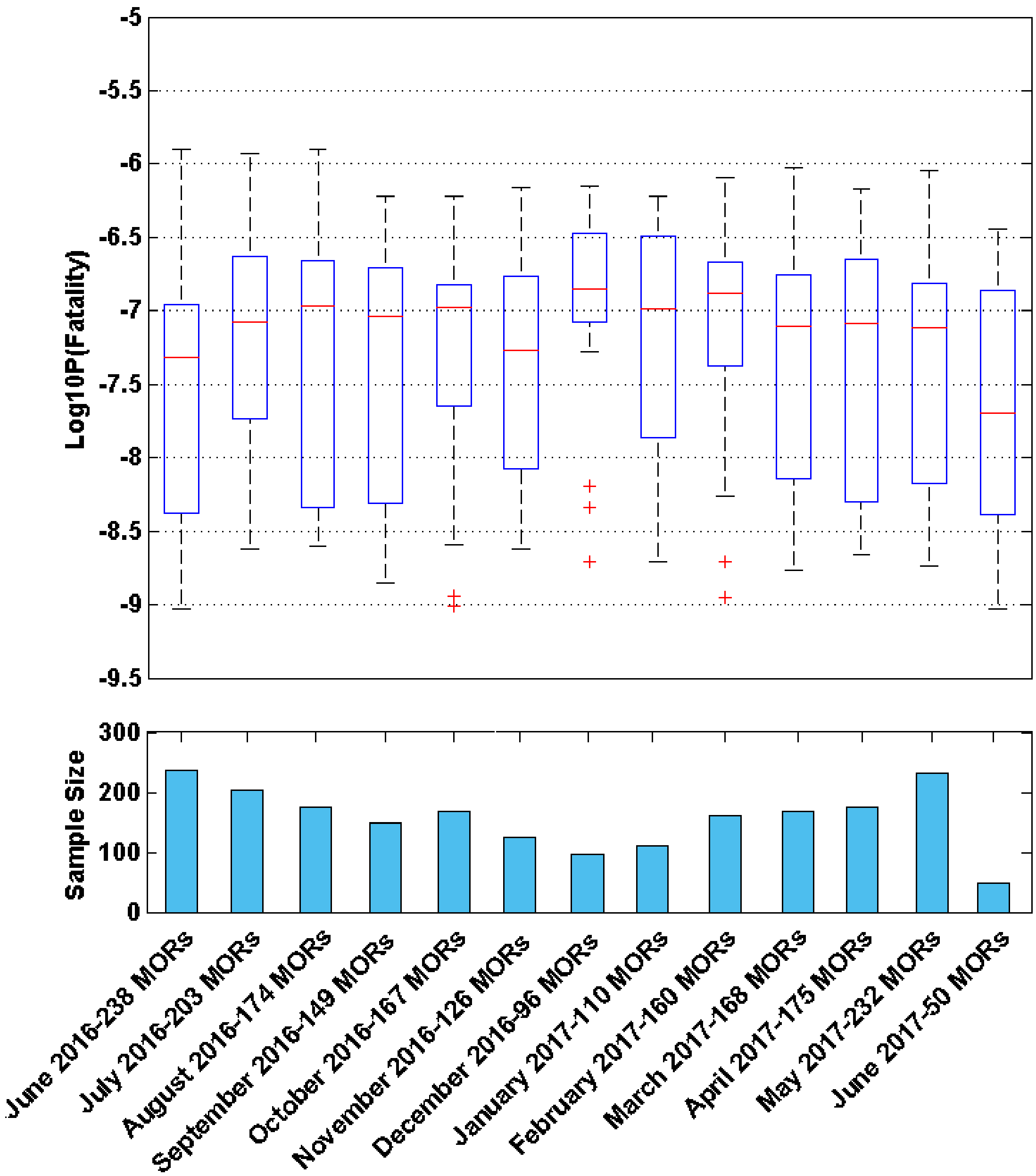


Figure 16. A snap shot of monthly P(Fatality) trends.[6]

[6] This dataset did not include June 1-4, 2016 and June 6-30, 2017.

The box-and-whiskers plot in Figure 16 shows MORs with P(Fatality) greater than zero plotted on a logarithmic scale. Table 8 shows sample size information for each month; 1) number of MOR were collected, 2) number of MOR that did not have all necessary data elements to complete the calculation, 3) number of MOR having P(Fatality) of zero, and 4) number of MOR having nonzero P(Fatality). . Note that 1,336 of 2,048 MOR (65%) had all necessary data elements to completed the calculation in the current method; 763 of 1,336 MOR (57%) had P(Fatality) of zero; and 573 of 1,336 MOR (43%) of MOR had nonzero P(Fatality). These results again show that the count of MORs cannot provide an indicator of risk in the NAS, rather, these events need to be analyzed so that the risk can be assessed and events above a specified threshold can be investigated and mitigation strategies developed and implemented.

Table 8. Monthly Sample Size Information.

Month	Total MOR	MOR Not Having All Necessary Data Elements	MOR with P(Fatality) = 0	MOR with P(Fatality) > 0
June 2016 (27 days)	238	85	68	85
July 2016	203	66	88	49
August 2016	174	57	67	50
September 2016	149	48	59	42
October 2016	167	61	63	43
November 2016	126	45	42	39
December 2016	96	35	40	21
January 2017	110	35	52	23
February 2017	160	62	72	26
March 2017	168	68	55	45
April 2017	175	56	67	52
May 2017	232	81	76	75
June 2017 (5 days)	50	13	14	23
Total	***2,048***	***712***	***763***	***573***

Individual and Collective Risk

FAA ATO has proposed using the Acceptable Level of Risk (ALR) approach to accommodate growth of new entrants into the NAS. The ALR approach "allows increased risk to specific aircraft operations, but limits overall exposure until the FAA modifies NAS infrastructure, policies, and procedures to integrate (new entrants)" (Bati, 2018; FAA, 2017). While there are pockets of higher risk in the NAS, the total number of predicted fatalities is extremely small compared to the number of NAS operations as a whole. Therefore it is reasonable to apply the ALR approach.

In the ALR approach, the safety standard is relaxed from 10^{-9} to P(Fatality) = 10^{-7} per ATC operation, but an upper limit is placed on the number of P(Fatality) values that can exceed one order of magnitude below that standard (10^{-8} in this case). The upper limit of operations with increased risk is derived by combining the equations in Bati (2018), resulting in the following:

- N = -ln(c) / (r*t) where
- N = upper limit of operations with increased risk per year
- c = confidence level that (k) or fewer fatalities will occur during the time period of evaluation
    - k = goal of zero fatalities during the time period of evaluation
- r = ALR safety standard of P(Fatality) = 10^{-7} per ATC operation
- t = time period of evaluation in years

After carrying out the calculation, (N) is compared to the number of P(Fatality) values above 10^{-8} to determine whether the ALR safety criterion is satisfied. In the current model, (c) is set to 99% confidence level that (k=0) fatalities will occur during the time period of evaluation (c=95% is also reasonable). (r) is 10^{-7} per ATC operation; and (t) is set to 80 years, approximately the length of an average human lifespan (to model mitigation of unexpected fatality caused by the new NAS entrant). In the current dataset, 217 P(Fatality) values over 10^{-8} were observed in a 176-day time period, which is extrapolated to 450 per year. This is compared to N = -ln(c) / (r*t) = 1,256 operations with increased risk per year with the listed assumptions.

The ALR criterion is satisfied for this dataset, but this may change as the small UAS population grows. However, technology, policy, and regulation will mature over time, providing further mitigations to P(Fatality). As safety mitigations mature, the FAA may revert from the ALR approach to the standard safety approach of 10^{-9} fatalities per ATC operation; the ALR approach is useful as risk acceptance standards are agreed upon and to accommodate industry growth for a new entrant to the NAS (FAA, 2017).

Areas of Refinement for the Model

Certain areas of refinement have been identified for this quantitative model. These areas should be considered for future enhancements. First, FAA has improved MOR data collection and presentation methods, one new data field is the “Relative Clock Position” from the manned aircraft pilot’s perspective. The level of estimated risk should be lowered when the manned aircraft is not heading directly towards the UAS. In fact, only a limited range of “Relative Clock Positions” can lead to mid-air collisions if manned aircraft speed is still assumed to be much higher than UAS speed. For example, Relative Clock Position = 3 indicates the UAS is just off the left wing of the manned aircraft, by the time the UAS is visually acquired, the manned aircraft will have already missed the UAS. Second, the number of observed MOR is currently used to represent the presence of UAS in proximity to manned aircraft. However, other data sources, such as those for the number of small UAS registrations, sales, and Part 107 authorizations are improving. When available, these data sources could be used to provide a more accurate estimate of UAS operations. Finally, aspects of the ALR approach could also be refined for more targeted risk assessments. For example, with sufficient data, the relative risks associated with large vs small UAS, specific airspace or geographical areas could be assessed and used to help inform operational decisions.

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