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Preliminary Risk Assessment for Small Unmanned Aircraft Systems

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Many beneficial civilian applications of commercial and public UAS in uncontrolled airspace have been proposed and are currently being demonstrated. Assessing and ensuring the safety of an emergent sUAS operation is a complex and difficult problem due to the numerous factors that must be considered. This paper provides an overview of past efforts regarding third party casualty estimation based on both single-vehicle collision with the ground and mid-air collision accidents. Next, the development of a preliminary risk analysis approach for small unmanned aircraft systems (sUAS) will be presented. Two approaches will be used in performing this analysis: (1) A Standard Risk Analysis approach, and (2) A Probabilistic Model-Based approach. The first approach uses a safety risk management process in which an analysis is conducted to identify hazards, along with their possible causes and any existing safety controls or proposed mitigation strategies, associated with proposed sUAS operational applications and use cases. The second approach uses a similar risk assessment architecture and investigates the feasibility of employing a comprehensive probabilistic model for risk estimation. The model is designed to be capable of capturing multi-factor interdependencies and their failure modes along with internal and external parameters, such as aircraft failure types, environmental factors, and mitigation strategies. The advantages of such a probabilistic model are threefold: (a) it provides a platform that allows the evaluation of various test scenarios, (b) it postulates acceptable system and component failure rates using the Target Level of Safety (TLS) approach, and (c) it identifies and estimates the effect of necessary risk mitigations in cases where obtaining the required reliability is not economically or operationally feasible.

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The risk analysis process is undertaken to provide assurances that the risks associated with the operation of unmanned aircraft systems have been managed to acceptable levels. The results of this safety risk analysis may be used to highlight important safety risks and issues, identify improvement opportunities, make recommendations concerning the elements of the system that are most likely to contribute to future problems, and identify safety requirements to include in the system requirements and performance documents.

Nomenclature

AGL	=	above ground level
BBN	=	Bayesian belief network
BVLOS	=	beyond visual line of sight
CFR	=	Code of Federal Regulations
COTS	=	commercial off-the-shelf
CPT	=	conditional probability table
FCS	=	flight control system
FW	=	fixed wing
MAC	=	mid-air collision
MR	=	multirotor
NAS	=	National Airspace System
NMAC	=	near mid-air collision
SRM	=	safety risk management
sUAS	=	small unmanned aircraft system
TLS	=	target level of safety
UAS	=	unmanned aircraft system
UH	=	unmanned helicopter
UTM	=	UAS Traffic Management
VLOS	=	within visual line of sight

I. Introduction

Unmanned Aircraft Systems (UAS) are an important and rapidly emerging sector of the aviation industry. Many beneficial civilian applications of commercial and public UAS in uncontrolled airspace have been proposed and are currently being demonstrated. These applications include imaging, construction, photography and video, precision agriculture, security, emergency/disaster response, law enforcement, search and rescue, mapping and surveying, infrastructure inspections and management, environmental research and conservation, communications, parcel delivery, and humanitarian efforts such as delivery of medical supplies in developing nations. The Unmanned Aircraft System (UAS) Traffic Management (UTM) Project seeks to facilitate the safe use of low-altitude airspace (below 400 feet) by small UAS (sUAS of 55 pounds or less) operators for a wide variety of applications. The goal of the UTM Safety element within UTM is to develop a methodology for assessing UTM safety risks and ensuring safe UTM operations.

Manned aircraft airworthiness is intended to provide safety for occupants of the aircraft and for others outside the aircraft, such as the population on the ground or occupants of other aircraft. Much of the airworthiness details are specific requirements for structural strength, stability, redundancy, etc. In the US, these are found in Title 14 Code of Federal Regulations (CFR) Parts 23[1], 25[2], 27[3], and 29[4]. In addition, Section 335 of the *FAA Modernization and Reform Act of 2012* [5] directs the FAA to "carry out all safety studies necessary to support the integration of unmanned aircraft systems into the national airspace system." Since by definition unmanned aircraft do not have occupants, requirements to protect passengers and crew (including crashworthiness, oxygen, and pressurization) need not be considered. Protection of others, both on the ground and in other aircraft must, however, be addressed. This is best handled by considering the risk of injury or death to people on the ground or in other aircraft. Currently, the airworthiness requirements consider risk only when dealing with onboard system failures, such as collision avoidance or other systems. The requirements specified in the Code of Federal Regulations are usually demonstrated by an analysis of the likelihood of injuries or fatalities with different requirements applying to light airplanes, transport aircraft, or helicopters. A similar set of requirements for unmanned aircraft systems (UASs) is needed as more commercial applications are becoming widespread.

Assessing and ensuring the safety of an emergent sUAS operation is a complex and difficult problem due to the numerous factors that must be considered. Associated with the proliferation of civil applications for sUAS is a paradigm shift from single-UAS remotely piloted within visual line of sight (VLOS) operations in remote locations to multi-UAS beyond visual line of sight (BVLOS) operations with increasing use of autonomous systems and operations under increasing levels of urban development and airspace usage. Under increasing levels of operational complexity and sophisitication come increasing complexity of hazards sources and levels of safety / risk impacts. Ensuring safety while considering these factors can be thought of as a multidimensional problem, and visualized in a 3-dimensional problem space as depicted in Fig. 1.

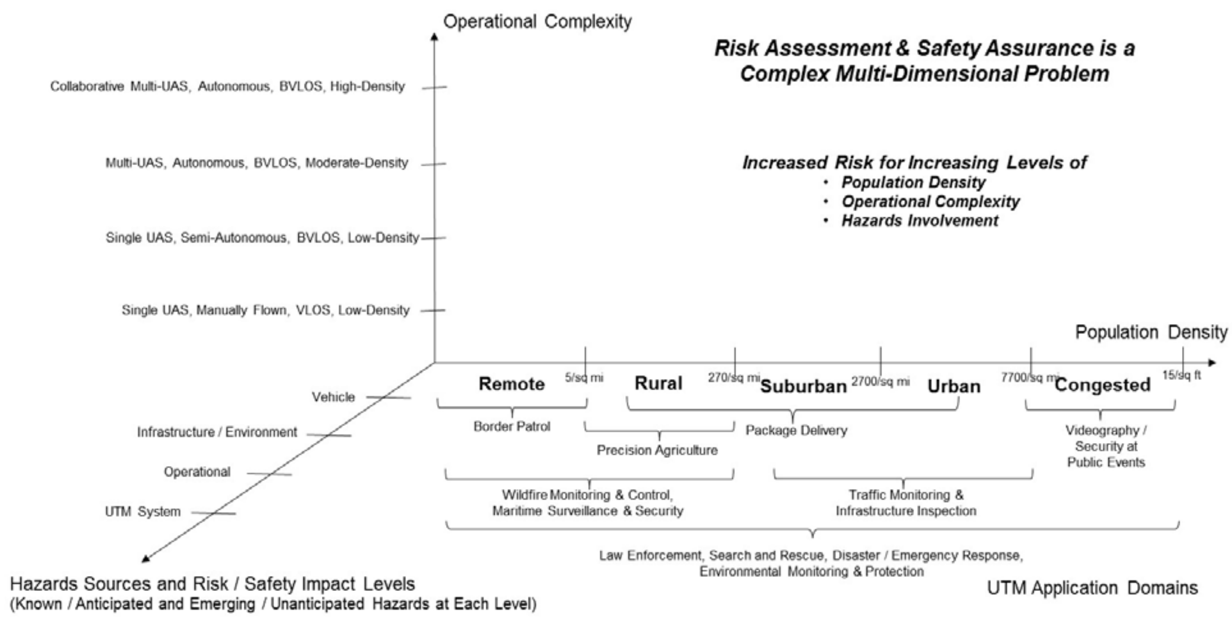


Figure 1. Multidimensional Problem Space for Assessing Risk and Ensuring the Safety of sUAS and UTM Operation[*]

As indicated in Fig. 1, one dimension of the safety problem involves operational complexity, which increases with increasing numbers of sUAS operations by a single operator, increasing use of autonomous systems and operations, and increasing density of operations within the UTM airspace (i.e., from low to high density of operations). Another dimension of the safety problem involves the operational environment in terms of population density (including remote, rural, suburban, urban, and congested), and the proliferations of applications for sUAS being considered. An attempt is made in Figure 1 at mapping the various sUAS appications (or use cases) across the operational environments envisioned. The third dimension depicted in Fig. 1 represents the hazards sources and levels of associated safety / risk impact, including those at the vehicle, infrastructure, environment, operational, and the UTM system levels. It should be noted that hazards at one level can affect not only that level but others along this dimension. For example, a hazard at the vehicle level can impact safety and risk at the operational level.

The introduction of a UAS operation into controlled airspace is a modification of the airspace system, and therefore requires risk analysis to ensure that an acceptable level of safety is maintained. Safety and risk assessments associated with UAS operations have been the subject of a number of publications.[6, 7, 8] This paper presents a preliminary safety risk assessment for sUAS operations that considers a portion of the problem domain of Fig. 1. The objective of this preliminary safety risk assessment is to develop risk analysis methods and models for assessing risk under off-nominal conditions at various levels of population density and operational environments and for various sUAS weight

[*] Population Densities from Demographia, http://www.demographia.com/db-intlsub.htm, downloaded 29 March 2016.

classifications and configurations. Two approaches for assessing the risk of operating small UAS in the National Airspace are presented in this paper, a standard safety risk management approach and a probabilistic model-based risk assessment approach. Mitigation measures are also developed to reduce risk where necessary and assure that the risk of operating sUAS in civilian airspace remains acceptably low.

The paper is organized as follows: Section II presents some risk analysis preliminary considerations, including definition of key terms, a description of the system and operational characteristics used in the preliminary risk assessment, and the technical approach; Section III discusses the standard safety risk management assessment approach and summarizes the results of the preliminary safety risk assessment; Section IV presents the probabilistic model-based risk assessment approach; and Section V presents a summary of the results, conclusions, and future work.

II. Risk Analysis Preliminaries

This section provides definitions, a depiction of the problem subspace being addressed in the preliminary risk assessment of this paper, and the technical approach.

A. Definitions[9]

Hazard – Any real or potential condition that can cause injury, illness, or death to people; damage to or loss of a system, equipment, or property; or damage to the environment. A hazard is a prerequisite to an accident or incident.

Accident – An unplanned event or series of events that results in death, injury, or damage to, or loss of, equipment or property.

Incident – An occurrence other than an accident that affects or could affect the safety of operations.

Cause – One or several mechanisms that trigger the hazard that may result in an accident or incident; the origin of a hazard.

Control – A current, planned, or proposed means to reduce or eliminate a hazard's causes or effects.

System State – An expression of the various conditions, characterized by quantities or qualities, in which a system can exist.

Effect – The real or credible harmful outcome that has occurred or can be expected if the hazard occurs in a defined system state.

Severity – The consequence or impact of a hazard's effect or outcome in terms of degree of loss or harm to include: death, injury, damage to or loss of equipment or property, damage to the environment, or monetary loss.

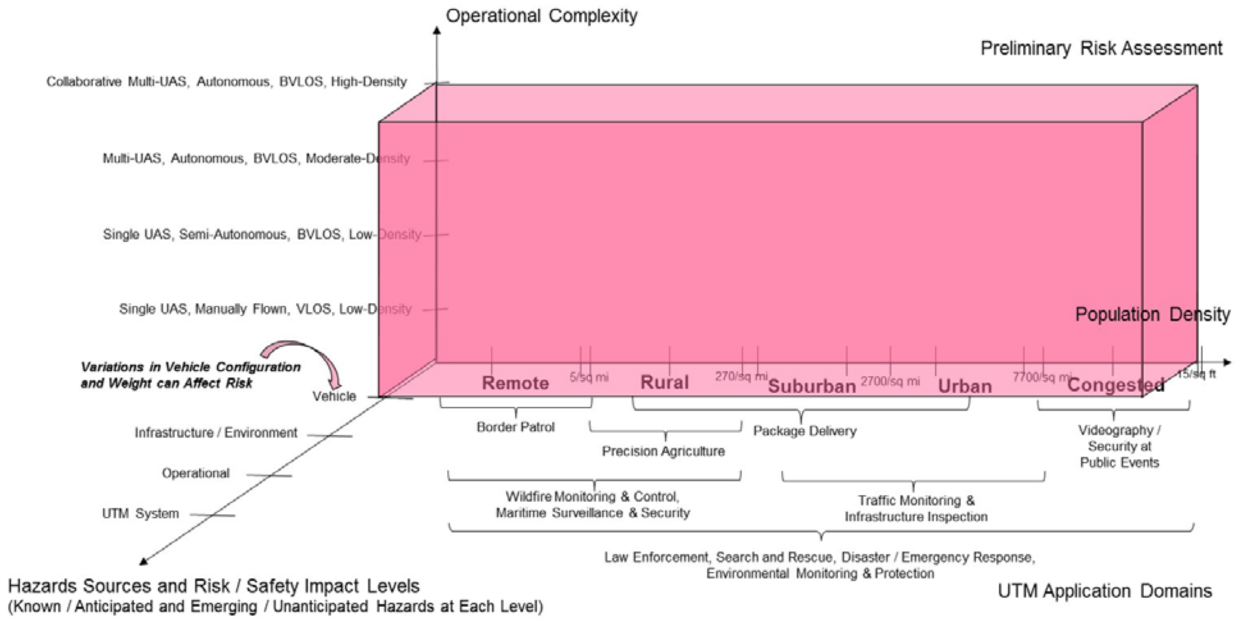
Likelihood – The estimated probability or frequency, in quantitative or qualitative terms, of a hazard's effect or outcome.

Risk (or Safety Risk) – The combination or composite of the predicted severity and likelihood of occurrence of a hazard's effect or outcome. The expected value of loss resulting from the hazard.

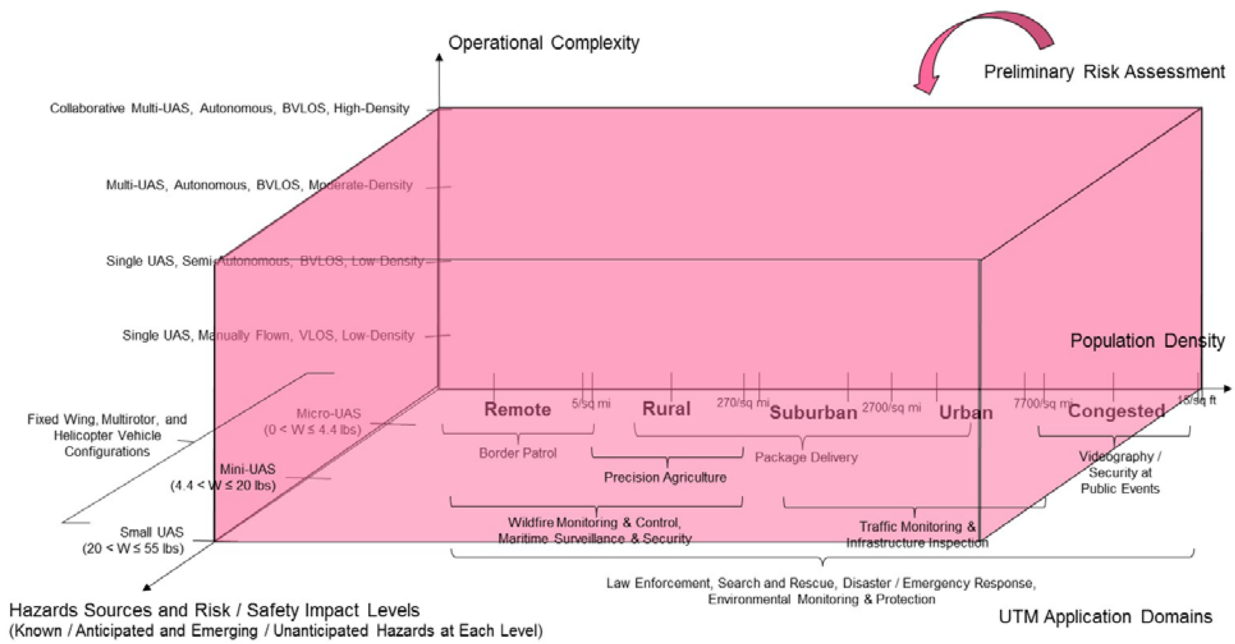
Mitigation Measure (or Safety Requirement) – Action required to reduce the associated risk by lessening the severity of the resulting mishap or lowering the likelihood that a mishap will occur.

B. Preliminary Risk Assessment Problem Subspace

As indicated in Fig. 2, the preliminary risk analysis presented in this paper considers the full "Population Density / UTM Application Domains" and "Operational Complexity" dimensions, but focuses on Vehicle-Level Hazards and associated risks along the third dimension. This focus was selected in order to consider various vehicle configurations and weight classes in the risk analysis. As depicted in Fig. 2b, the vehicle focus considered herein includes three weight and configuration classes of sUAS. These sUAS classes will be discussed further in Section III.B.1. Future analyses will consider the full "Hazards Sources and Risk / Safety Impact Levels" dimension.



a. Problem Subspace Addressed in the Preliminary Risk Assessment of this Paper

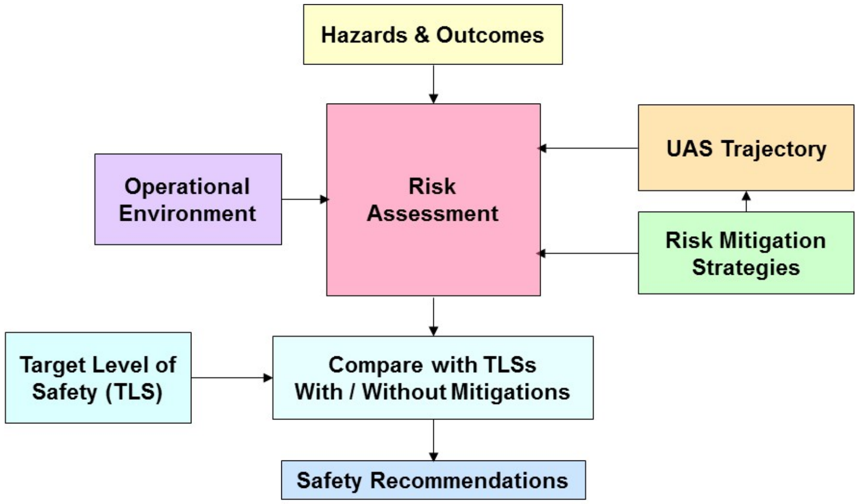


b. Problem Subspace Showing an Expanded Vehicle Scale

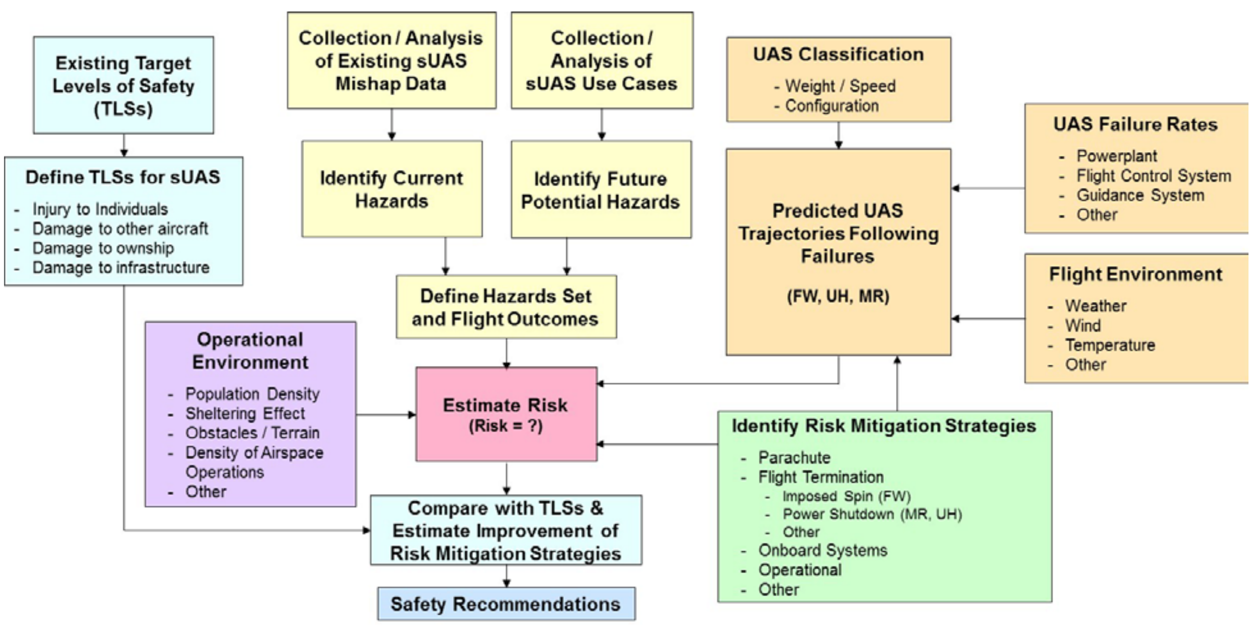
Figure 2. Problem Subspace Addressed by the Preliminary Risk Assessment of this Paper

C. Risk Assessment Approach

The risk assessment approach is described in this section and illustrated in Fig. 3. The risk assessment process considers hazards, their outcomes, and the operational environment (e.g., population density, airspace density of operations), and determines the associated level of risk based on the trajectory at impact (e.g., to people on the ground or to manned aircraft) and the effectiveness of any mitigation strategies that have been implemented. The level of risk can be compared to a target level of safety with and without the use of mitigations. The assessment of risk can lead to safety recommendations for reducing risk and improving safety. These basic steps are illustrated in Fig. 3a.



a. High-Level Risk Assessment Approach



b. Detailed Risk Assessment Approach

Figure 3. Block Diagram Depicting the (a.) High-Level and (b.) Detailed Risk Assessment Approach Used in this Paper

Fig. 3b expands on the basic risk analysis steps of Fig. 3a in order to illustrate the approach being taken herein to address each step in the process. An extensive hazards analysis was performed[10] for sUAS to identify and assess both current hazards (based on an analysis of sUAS mishaps) and future potential hazards (based on an identification of paradigm shifts and associated hazards arising from future sUAS use cases of operation). From these analyses, a combined set of hazards was identified (see Section III.A) for use in assessing risk. Trajectory prediction for sUAS under off-nominal conditions is based on vehicle dynamics simulation models capable of characterizing off-nominal condition effects on flight dynamics and control characteristics. The off-nominal conditions include onboard system failures, vehicle impairment conditions, wind and inclement weather conditions. This has been a significant effort for multirotor vehicles[11] where the availability of flight validated data for flight dynamics and control modeling has been limited. Failure rates are also difficult to determine for sUAS due to the wide variety of components and limited available information, but must be accounted for in the risk assessment. Weight and configuration of sUAS can also impact risk, so three vehicle configurations and weight classes were defined (see Section III.B). A number of operational factors were also considered, including population density, sheltering effect (e.g., are the people inside buildings or out in the open), obstacles and terrain features, density of airspace operations, etc. Risk mitigation strategies to be considered include the use of a parachute, flight termination systems, onboard hazards mitigation systems, operational risk mitigation strategies, etc.

Target Levels of Safety (TLS) for aircraft are based on systems certification regulations, such as 14CFR §23.1309 for small airplanes[1] or 14CFR §27.1309 for small rotorcraft.[3] Recommended TLS have been adapted from the FAA Advisory Circulars[12] [13] for these two regulations.

III. Standard Safety Risk Management Assessment

Ensuring the safety of sUAS operations requires an understanding of associated current and future hazards and their associated risks. The Safety Risk Management (SRM) process provides an accepted and systematic means for providing assurances that the risks associated with UAS operations have been managed to an acceptable level. The SRM process and its outcomes form part of a documented safety case necessary to obtain approvals for UAS operations. Our process for system safety is derived from the framework of a safety risk management plan, e.g., as recommended in MIL-STD-882E, the National Aeronautics and Space Administration (NASA) Facility System Safety Guidebook, the Federal Aviation Administration (FAA) System Safety Handbook, or the FAA Safety Management System Manual. The objective of the risk assessment process is to comprehensively characterize the safety risks associated with UAS operations, and based on this information, determine which of the identified risks can be tolerated and which risks require mitigation (treatment). The objective of the risk treatment process is to identify, implement, and evaluate suitable measures to reduce (mitigate, modify, treat, or control) the risk.

A typical starting point for any risk identification process is a review of existing accident and incident data. Such a review can provide general insights into the key hazards and their likely consequential outcomes and, depending on the scope and quality of the investigative reports available, the factors contributing to their occurrence. This is challenging for sUAS operations, however, due to insufficient mishap (accident and incident) reporting for sUAS and the proliferation of new sUAS use cases that have not yet been implemented. Seldom does a review of accident and incident data provide a “comprehensive” identification of the potential hazards and their outcomes. This is particularly the case for UAS, where limited data are available and the primary hazards are inherently rare events. Further, the ability to identify the complexity of factors contributing towards the occurrence of an accident or incident is often restricted by the method and quality of the records available. Nevertheless, we were able to use the information available in several reports of sUAS mishaps, accidents, and incidents in our hazard identification and risk analysis process. We also relied upon use cases collected from NASA UTM partner companies, the Department of Homeland Security, the Department of the Interior, and a review of the literature describing proposed sUAS mission applications.

A. Preliminary Hazards Set

As indicated in Fig. 3 by the yellow blocks, an important preliminary step in assessing risk is to identify the hazards to be assessed. The approach taken was to identify current hazards based on an analysis of sUAS mishaps, and to identify future potential hazards by analyzing sUAS use cases collected from industry and government agencies. From these analyses, a combined list of hazards was developed.**[10]** The full set of combined hazards is provided in Appendix

A. For the preliminary risk assessment of this paper, the first seven vehicle level hazards are analyzed. This hazards set is provided in Table 1.

Table 1. Vehicle-Level Hazards Set Considered in the Prelminary Risk Analysis

Hazard No.	Hazard
VH-1	Aircraft Loss of Control (LOC)
VH-2	Aircraft Fly-Away / Geofence Non-Conformance
VH-3	Aircraft Lost Communication / Control Link
VH-4	Aircraft Loss of Navigation Capability
VH-5	Unsuccessful Landing
VH-6	Unintentional / Unsuccessful Flight Termination
VH-7	Failure / Inability to Avoid Collision with Terrain and/or Fixed / Moving Obstacle

Each hazard in the above set is assessed along the "Population Density / UTM Application Domains" and "Operational Complexity" dimensions of Fig. 2. These are discussed further in the next section.

B. Qualitative Risk Assessment

A qualitative risk assessment of the hazards listed in Table 1 was conducted. Each hazard was considered in terms of all three dimensions of the problem space illustrated in Fig. 2b – operational complexity, population density, and vehicle weight and configuration. In addition, each hazard was described in terms of possible causes and considered in terms of credible outcomes.

The risk assessment considered five operational environments: Remote, rural, suburban, urban, and congested. Additionally, we analyzed the risks associated with three vehicle weight classes as shown in Table 2: Micro UAS ($W \leq 4.4$ lbs), Mini UAS ($4.4 < W \leq 20$ lbs), and Small UAS ($20 < W \leq 55$ lbs). And finally, three sUAS vehicle configurations were evaluated: fixed wing (FW), multirotor (MR), and unmanned helicopter (UH).

1. sUAS Classification

It is likely that any unmanned aircraft classification will be centered on the UAS's mass and speed (i.e., on its kinetic energy). We have chosen maximum speeds proposed by the Small Unmanned Aircraft System Aviation Rulemaking Committee (sUAS ARC) for UAVs up to 55 pounds.[14] [15] The specific groupings used within this paper are shown in Table 2.

Table 2. UAV Classes

UAV Class	Weight, max [lb]	Velocity, max [knots]	Kinetic Energy, max [ft-lb]
A: Micro-UAS	4.4	60	704
B: Mini-UAS	20	87	6,727
C: Small UAS	55	87	18,498

2. Severity Categories

Manned aircraft system failures are defined in terms of their effect on both the aircraft and on persons.[16] *Catastrophic* hazardous effects involve multiple fatalities, loss of the aircraft, or incapacitation of the flight crew. A *hazardous* event (sometimes referred to as a *severe major* hazard) is one that involves a serious or fatal injury to an aircraft occupant, a large reduction in the functional capabilities of the aircraft, a large reduction in safety margins, or physical distress or excessive workload that impairs the ability of the crew to perform tasks. A *major* hazard involves physical distress for passengers, significant reduction in safety margins, or significant increase in crew workload. A *minor* hazard involves physical discomfort for passengers, slight reduction in safety margins, or slight increase in crew workload.[12 13]

We have adapted these definitions for unmanned aircraft, omitting any reference to aircraft occupants.[17] Also, we do not consider damage to the UAS itself. For unmanned aircraft, the severity categories used in our qualitative safety risk assessment are shown in Table 3.[12]

Table 3. Proposed Hazard Severity Categories

Severity Category	Injuries	Safety Margins	Crew Workload
(1) Catastrophic	Multiple Fatalities		
(2) Hazardous	Single Fatality and/or Multiple Serious Injuries	Large Decrease	Compromises Safety
(3) Major	Non-Serious Injuries	Significant Decrease	Significant Increase
(4) Minor	None	Slight Decrease	Slight Increase
(5) No Safety Effect	None	No Effect	No Effect

3. Likelihood Classes

Likelihood is defined as the estimated probability or frequency of a hazard's effect or outcome. Quantitative allowable probabilities for manned airplane hazards are taken from the various FAA system safety Advisory Circulars.[12, 13] It should be noted that these are not exact values; the requirements for the allowable probabilities indicate an order of the listed value.

The allowable probabilities for small airplanes differ from other aircraft by several orders of magnitude. At this juncture, it is not clear if sUAS using rotors will be held to a higher standard than fixed wing UAS. For this study, we elected to use the small airplane standards. In designing systems for collision avoidance, small airplanes are not allowed any relaxation of the catastrophic probability.[18]

The quantitative and qualitative likelihood classifications used in the risk analysis are shown in Table 4.[12]

Table 4. Likelihood Classes Used in the Risk Analysis

Likelihood Class	Allowable Probability			
	Quantitative			Qualitative
	Small Airplane	Small Helicopter	Any Midair Collision	
(A) No Probability Requirement	No Probability	No Probability	No Probability	No requirement on frequency of occurrence
(B) Probable	$< 10^{-3}$	$< 10^{-3}$	—	Will occur several times in the life of an aircraft

(C) Remote	$< 10^{-4}$	$< 10^{-5}$	—	Likely to occur once in the life of an aircraft
(D) Extremely Remote	$< 10^{-5}$	$< 10^{-7}$	—	Unlikely, but possible to occur in the life of an aircraft
(E) Extremely Improbable	$< 10^{-6}$	$< 10^{-9}$	$< 10^{-9}$	It can be assumed that occurrence will not happen

4. Risk Matrix

The risk matrix shown in Fig. 4[9] is used to assign a risk level for each identified hazard based on the hazard effect's severity and likelihood. High risk is unacceptable, and any proposed operational changes in the NAS cannot be implemented unless the hazard's associated risk is mitigated to medium or low.

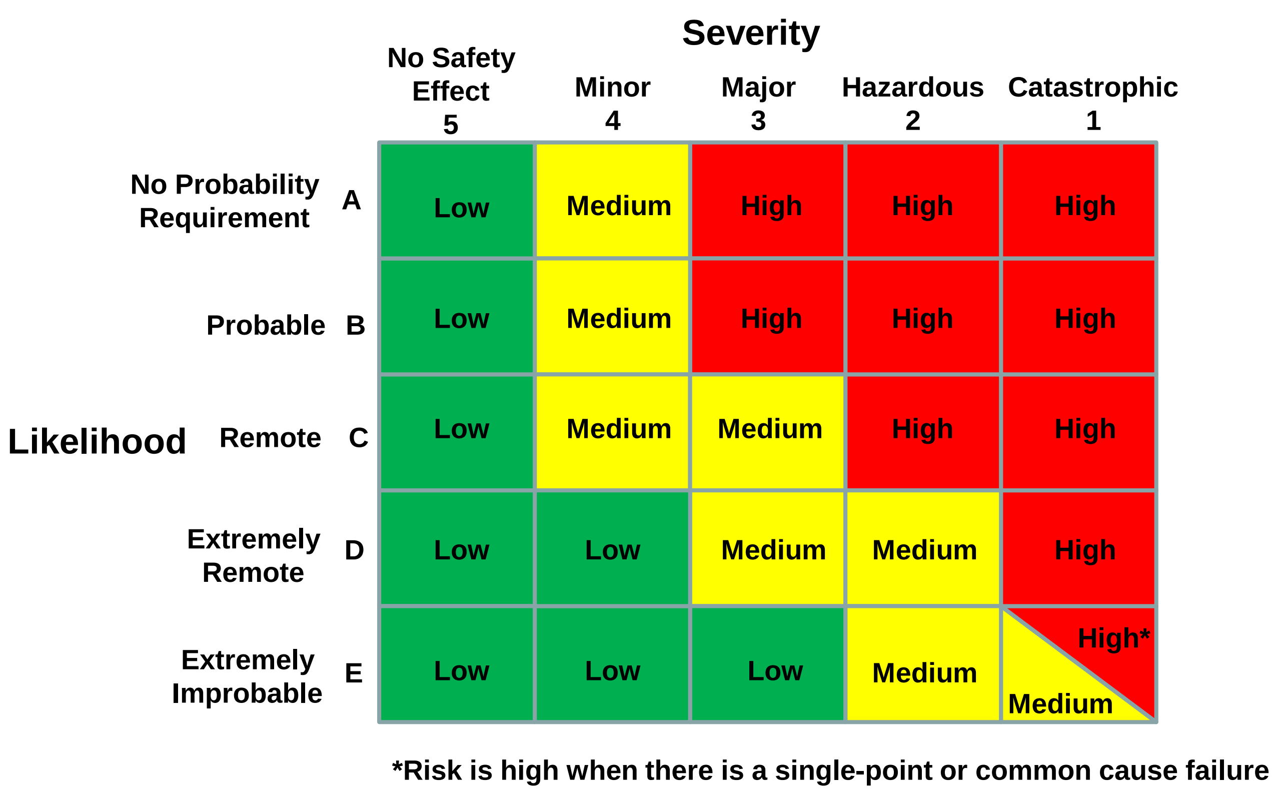


Figure 4. Risk Matrix Used for Analysis

5. Results

A discussion of how we applied the standard risk assessment process to the evaluation of the aircraft loss of control hazard (VH-1 of Table 1) is presented in this section. The results of the risk assessment of aircraft loss of control is shown in Tables 5a, b, and, c for low-density single manually controlled UAS operations in Remote/Rural areas, moderate-to-high density semi-autonomous operations with a single UAS in Suburban/Urban areas, and semi-/fully-autonomous operations of one or multiple UAS in moderate-to-high density airspace in congested conditions, respectively. A summary of the risk assessment results for the remaining six hazards of Table 1 is included in Appendix B.

Hazard Causes/Contributing Factors: Possible causal and contributing factors to the aircraft loss of control hazard include:

- Vehicle Failures / Impairment
- Control System Failures / Malfunctions / Inadequacy
- Propulsion System Failure / Malfunction
- Weather (Includes Rain, Snow / Icing, Thunderstorms, etc.)
- Wind / Wind Shear / Turbulence (Includes Boundary Layer Effects)
- Vehicle Upset Condition / Damage
- Pilot Error
- Power Loss / Fuel Exhaustion
- Electromagnetic Interference (EMI)
- Unsuccessful Launch
- Flight Control System Design / Validation Errors / Inadequacy
- Flight Control System Software Implementation / Verification Error / Inadequacy
- Bird Strike
- Payload / CG Shift / Instability
- Unexpected Obstacle Encounter Results in Unstable / Aggressive Avoidance Maneuver
- Boundary Layer Wind Effect
- Inadequate Resilience in Flight Control System to Key LOC Hazards (Including Failures, Wind / Weather, etc.)
- Vehicle Damage (e.g., Lightning strike during long-duration missions, damage from explosion / fire during emergency response, etc.)
- Harsh Environmental Conditions (e.g., Extreme temperatures, etc.)
- Cascading Factors Involving Multi-UAS Operations

Hazard Effects: A safety risk management analysis must always assess the risk of the worst credible outcome. However, other possible effects should also be considered, particularly if their higher likelihood of occurrence could lead to a higher risk. Three possible effects (PE) or outcomes resulting from a loss of control were identified:

- PE-1: Undesired flight trajectory and/or uncontrolled descent could cause the aircraft to potentially collide with another UAS or a manned aircraft operating in the area.
- PE-2: Undesired flight trajectory and/or uncontrolled descent could result in striking a person on the ground causing injury or fatality.
- PE-3: Undesired flight trajectory and/or uncontrolled descent could cause the aircraft to potentially crash into a building/obstacle resulting in secondary injury from UAS debris or building damage.

Other possible effects involve UAS loss and property damage resulting from a collision with terrain or a structure. These outcomes were not considered in the safety risk analysis since their primary impacts are economic (loss of aircraft, damaged property, mission loss) rather than safety related.

Severity of Hazard Effects: Our estimations of severity for each of the three possible effects are shown in Tables 5a, b, and c. These represent our qualitative, consensus-based determinations based on knowledge of past sUAS mishaps as well as consideration of projected future sUAS applications and operating environments. The severity levels used in the assessment are defined in Table 3.

Table 5. Preliminary Risk Assessment Summary

a. Remote/Rural, Low-Density, Single UAS Operations

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-1 Aircraft Loss of Control Operating Environment: • Remote/Rural Location • Low-Density Operations • Single UAS • Manual Control by Pilot • VLOS / BVLOS	PE-1: Undesired flight trajectory and/or uncontrolled descent could cause the aircraft to potentially collide with another UAS or a manned aircraft operating in the area. PE-2: Undesired flight trajectory and/or uncontrolled descent could result in striking a person on the ground causing injury or fatality. PE-3: Undesired flight trajectory and/or uncontrolled descent could cause the aircraft to potentially crash into a building/obstacle resulting in secondary injury from UAS debris or building damage.	Micro UAS (0 < W≤ 4.4 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
		Mini UAS (4.4 < W ≤ 20 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
		Small UAS (20 < W ≤ 55 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Extremely Remote

Table 5. Preliminary Risk Assessment Summary

b. Suburban/Urban, Moderate-to-High Density, Single UAS Operations

<table>
<tr><th>Hazard Description</th><th>Possible Effects</th><th>Vehicle Weight Class</th><th>Vehicle Configuration</th><th>Severity</th><th>Safety Objective</th></tr>
<tr><td rowspan="9">VH-1
Aircraft Loss of Control

Operating Environment:
• Suburban / Urban Location
• Moderate-to-High-Density Operations
• Single- or Multi-UAS Operations
• Semi-Autonomous Control
• BVLOS</td><td rowspan="9">PE-1. Potential for LOC involving multiple UAS under common causal conditions (e.g., unexpected wind / weather) resulting in midair collision with other UAS/manned aircraft and potentially one or more injuries/fatalities.

PE-2: Undesired flight trajectory and/or uncontrolled descent of multiple UAS could result in striking multiple persons on the ground causing injury or fatality.

PE-3. Undesired flight trajectory and/or uncontrolled descent by multiple UAS could cause multiple crashes into a building/obstacle resulting in secondary injury from UAS debris or building damage.</td><td rowspan="3">Micro UAS
(0 < W≤ 4.4 lbs)</td><td>Fixed Wing</td><td>PE-1: Catastrophic
PE-2: Catastrophic
PE-3: Major</td><td>PE-1: Extremely Improbable
PE-2: Extremely Improbable
PE-3: Remote</td></tr>
<tr><td>Multirotor</td><td>PE-1: Catastrophic
PE-2: Catastrophic
PE-3: Major</td><td>PE-1: Extremely Improbable
PE-2: Extremely Improbable
PE-3: Remote</td></tr>
<tr><td>Helicopter</td><td>PE-1: Catastrophic
PE-2: Catastrophic
PE-3: Major</td><td>PE-1: Extremely Improbable
PE-2: Extremely Improbable
PE-3: Remote</td></tr>
<tr><td rowspan="3">Mini UAS
(4.4 < W ≤ 20 lbs)</td><td>Fixed Wing</td><td>PE-1: Catastrophic
PE-2: Catastrophic
PE-3: Major</td><td>PE-1: Extremely Improbable
PE-2: Extremely Improbable
PE-3: Remote</td></tr>
<tr><td>Multirotor</td><td>PE-1: Catastrophic
PE-2: Catastrophic
PE-3: Major</td><td>PE-1: Extremely Improbable
PE-2: Extremely Improbable
PE-3: Remote</td></tr>
<tr><td>Helicopter</td><td>PE-1: Catastrophic
PE-2: Catastrophic
PE-3: Major</td><td>PE-1: Extremely Improbable
PE-2: Extremely Improbable
PE-3: Remote</td></tr>
<tr><td rowspan="3">Small UAS
(20 < W ≤ 55 lbs)</td><td>Fixed Wing</td><td>PE-1: Catastrophic
PE-2: Catastrophic
PE-3: Hazardous</td><td>PE-1: Extremely Improbable
PE-2: Extremely Improbable
PE-3: Extremely Remote</td></tr>
<tr><td>Multirotor</td><td>PE-1: Catastrophic
PE-2: Catastrophic
PE-3: Major</td><td>PE-1: Extremely Improbable
PE-2: Extremely Improbable
PE-3: Remote</td></tr>
<tr><td>Helicopter</td><td>PE-1: Catastrophic
PE-2: Catastrophic
PE-3: Hazardous</td><td>PE-1: Extremely Improbable
PE-2: Extremely Improbable
PE-3: Extremely Remote</td></tr>
</table>

Table 5. Preliminary Risk Assessment Summary (continued)

c. Suburban/Urban/Congested, Moderate-to-High-Density, Single/Multi-UAS Operations

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-1 **Aircraft Loss of Control** Operating Environment: • Suburban / Urban / Congested Locations • Moderate-to-High-Density Operations • Single- or Multi-UAS Operations • Semi- or Fully-Autonomous Control • BVLOS	PE-1. Undesired flight trajectory could cause collision with other UAS or manned aircraft and an uncontrolled descent or landing could cause serious injury to many persons on the ground and possible fatalities. PE-2: Undesired flight trajectory and/or uncontrolled descent involving multiple UAS could result in widespread injuries / fatalities to persons on the ground. PE-3. Potential for LOC involving multiple UAS under common causal conditions or from design / validation inadequacy that affects multiple UAS and multi-UAS operations could cause multiple UAS to crash into a one or more buildings /obstacles resulting in widespread secondary injury from UAS debris and / or building damage.	Micro UAS (0 < W≤ 4.4 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Mini UAS (4.4 < W ≤ 20 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Small UAS (20 < W ≤ 55 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote

- PE-1: The Catastrophic severity rating was assigned to this hazard based on the possibility of a collision with a manned aircraft causing a fatal injury to one or more persons onboard. This is the worst credible outcome for remote/rural low-density operations as well as suburban/urban/congested areas in high-density airspace and for UAS in all weight classes and configurations. In rural and remote areas, it is more likely that the manned aircraft involved in the collision would be a small, private fixed wing aircraft (e.g., a crop duster) or a helicopter operating at low altitude rather than commercial transports. However, in high density airspace, for example approaches to busy airports, commercial air carrier pilots have been reporting passing and flying under UAS.
- PE-2: In a remote or rural area, we concluded that the possible effect of a loss of control striking a person on the ground has a severity level of Hazardous because we felt that the worst credible outcome would be a single fatality from the UAS striking a UAS crew member. However, as the operational complexity of sUAS operations increases – that is, for suburban/urban locations with multiple UAS being operated semi- or fully-autonomously in BVLOS operations – there is the potential for a UAS to strike and cause a fatal injury to several persons on the ground. Thus, the severity for this hazard effect under these conditions is Catastrophic.
- PE-3: Falling debris resulting from a UAS control loss and subsequent crash into a building has the potential for causing injuries to people on the ground. The number of people injured and the severity of their injuries depends greatly on the population density in the area of UAS operations, the number of UAS operating in the area (single vs. multiple operations), and the vehicle weight class. In remote/rural locations, the severity was determined to be Minor for micro-UAS but Major for the larger classes of vehicles between 4.5 and 55 pounds. In addition, we assigned a Major severity rating for more densely populated areas and more complex UAS operations because of the potential for injury to several people on the ground under these conditions. It is important to note that these severity levels assume that no post-impact fire occurs after the crash. However, for small UAS between 20 and 55 pounds, the severity level increases to Hazardous. The rationale for this higher severity outcome is that a post-impact fire is more likely for heavier fixed wing and helicopter UAS because they are more likely to be fueled by gasoline, and the fire in combination with falling debris increases the opportunity for multiple serious injuries to people on the ground.

Safety Objective: The objective of any safety risk assessment is to ensure an acceptable safety level for equipment and systems installed, services provided, or procedures implemented in the National Airspace System (NAS). Safety objectives represent the establishment of worst case hazard severities setting the greatest acceptable likelihood that would result in a risk level no greater than "medium" for each hazard. A logical and acceptable inverse relationship must exist between the likelihood of a failure occurrence and the severity of the hazardous effect such that outcomes having a higher severity must have a correspondingly lower likelihood of occurrence to yield and acceptable level of safety. Referring to the Risk Matrix in Fig. 4, a Catastrophic outcome must be Extremely Improbable ($< 10^{-6}$ for small airplanes) to achieve an acceptable level of risk. Similarly, Hazardous outcomes must be no more likely than Extremely Remote ($< 10^{-5}$), and Major outcomes must have likelihood levels of Remote or lower ($< 10^{-4}$).

C. Numerical Risk Assessment

This subsection presents an illustrative example related to VH-1: Aircraft Loss of Control based on an initial approach developed for sUAS.[16] More specifically, some of the assumptions and sources of the failure rates used in the risk assessment of this paper will be presented.

1. *Flight Environment*

We can now arrive at overall system reliabilities for selected system failures related to VH-1. In particular, we will use the following generic system failure rates:

Small Electric Motors: [19]	8.0×10^{-5}
Small Piston Engines: [20]	1.5×10^{-4}

Flight Control System (Predator): [21] 2.5×10^{-4}

We have not considered loss of Global Positioning System (GPS) signals, which can be quite significant in urban settings. We were unable to locate any representative data in the open literature. The loss-of-control conclusions must be tempered with this limitation, which would make urban data non-conservative.

2. Resulting Trajectories

Ultimately, trajectories will be generated using simulation models that characterize sUAS dynamics under off-nominal conditions. [11, 22, 23] For illustrative purposes, we adopted the simplified trajectory set which uses the small sample of sUAS mishaps considered in Ref. [16].

The outcomes of Flight Control System (FCS) failures was described in Reference [16] for 19 cases. That sample of 19 FCS failures showed that ten failures (53%) caused an unguided trajectory (shallow trajectory or flyaway), while nine (47%) caused an out-of-control descent (steep trajectories).

There was a marked difference with the type of sUAS. All propulsion system failures (4 failures) in quadrotor UASs led to uncontrolled descent. All of the other configurations led to controlled descent (3 failures), usually ending in a forced landing or collision with terrain.

Controlled descent (shallow trajectory; no flyaways):	100%	(FW UAVs or UH)
Uncontrolled descent (vertical, tumbling descent):	100%	(Quadrotor UAVs)

Navigation system failures (8 failures) led to 6 undesired trajectories usually ending with collision with terrain or obstacles. Two led to a safe outcome.

Unguided trajectory (shallow trajectory or flyaway):	75%
Safe outcome:	25%

3. Example Result for Quadrotor Striking a Person on the Ground

For illustrative purposes, we will now determine the probability of an errant quadrotor striking a person on the ground as a result of VH-1 caused by FCS component failures. This will require an estimation of the density of persons on the ground. We will consider five cases: A congested area, such as attending a sporting event, an urban environment, a suburban environment, a rural setting, and a remote setting.

Urban (7700 persons/sq mi) and Suburban (2700 persons/sq mi) density figures were obtained from *Demographia*[24]. Rural population densities were estimated to be ten percent of suburban densities and remote areas were estimated to be 5 persons per square mile. The population density of congested areas was based on an assumption of one person per fifteen square feet.

To calculate the probability that a UAV will strike a person, we need to determine the number of people per square foot times the cross section of the person. The basic assumption is that the trajectory of the errant UAV is random, either a shallow (near horizontal) or steep (near vertical) trajectory. We considered trajectories striking the person's body (presumably non-fatal) and a person's head (presumably fatal). For vertical descents of small objects, the approximate cross-section of a person is about $A_P = 1.5\ ft^2$. For a shallow-angle descent, the approximate cross-section is about $A_P = 11\ ft^2$. The approximate cross-section of a person's head is roughly $0.56\ ft^2$ for both shallow and steep trajectories. The result is:

$$P_{SP} = D_P \times A_P$$

Where P_{SP} = Probability of striking a person,
D_P = Population density (persons/ft^2), and
A_P = Cross section area of a person's body or head (as appropriate)

This applies to a small compact UAV such as a multirotor. Thus, the chance of a person being struck by a quadrotor is shown in Table 6. This table shows the probability of striking a person given the probability of a flight control or other failure resulting in the undesired trajectory. The probabilities are based on random shallow (near horizontal) and steep (near vertical) trajectories striking standing persons on the ground. For other types of unmanned aircraft, such as unmanned helicopters or fixed wing aircraft, we must adjust these probabilities to account for the larger size of the UAV.

Table 6. Percent of Quadrotor Impacts Striking Persons

Population Environment	Population Density	Striking Body		Striking Head	
		Vertical Trajectory	Horizontal Trajectory	Vertical Trajectory	Horizontal Trajectory
Congested	1 per 15ft^2	10%	73%	3.75%	3.75%
Urban	7700 per mi^2	0.04%	0.03%	0.02%	0.02%
Suburban	2700 per mi^2	0.01%	0.11%	0.01%	0.01%
Rural	270 per mi^2	~0	0.01%	~0	~0
Remote	5 per mi^2	~0	~0	~0	~0

The data in Table 6 show that for a vertical trajectory, we would expect that a UAV would strike a person (causing an injury) ten percent of the time in a congested area, but only 0.04% in a general urban environment, 0.01% in a suburban environment, and nearly zero in rural and remote areas. The figures for striking a person in the head (presumably fatal) would be 3.75% in a congested area and 0.02% in a general urban environment, etc. These conditional probabilities will be multiplied by the failure rates of the FCS system itself.

Thus, the probability of striking a person in the head (presumably fatal) in a congested area would be:

Unguided trajectory: $2.5\times10^{-4} \times 0.53 \times 0.02\% = 2.65\times10^{-8}$
Out-of-control descent: $2.5\times10^{-4} \times 0.47 \times 0.02\% = 2.35\times10^{-8}$

Together, the rate of the UAV striking a person in the head would be 5.0×10^{-8}. This rate should be compared with the Target Level of Safety (TLS) to determine acceptability. In this case, it meets the standards for light airplanes ($< 10^{-6}$), but not for light helicopters ($<10^{-9}$).

D. Mitigation Strategies

Currently, operational mitigation strategies such as restrictions on the flight of sUAS over populous areas, at altitudes above 400 feet AGL, beyond visual line of sight, and at nighttime are critical to obtaining operational approvals. Mitigation technologies, like sense-and-avoid and automated emergency landing systems, are currently under development and showing much promise. Other advanced technologies to be considered include resilient flight control systems capable of preventing and recovering from aircraft loss of control. These mitigation technologies will reduce the need for restrictions on UAS operations and will be key to the increase of UAS in a greater number of civil applications. We also identified the following measures that could be undertaken to mitigate, treat, or control the risk of sUAS operations to acceptable levels:

- Parachute
- Flight termination system
- Flight control redundancy (Control effector and/or computational)
- Electrical power source redundancy
- UASs operating BVLOS shall be equipped with Automatic Dependent Surveillance – Broadcast (ADS-B) Out transponders to enable their detection by ground-based ADS-B Out receivers.
- Rigorous pre-flight equipment/maintenance checks and flight planning.
- Pre-defined emergency/contingency procedures that enable pilot to force the UAV to land in a safe area in the event of a system or component failure or malfunction.

The impact of these mitigations on reducing risk will be considered in future work.

E. Summary and Key Findings

The objective of this section was to present some sample results from a preliminary qualitative risk assessment of operating sUAS in civil airspace using a standard safety risk management approach. Using reports of observed sUAS accidents and incidents as well as proposed future use case applications for these vehicles, a set of vehicle-level hazards were identified along with their possible causal and contributing factors. We then employed a qualitative, consensus-based process for evaluating the safety risk of the potential effects or outcomes of these hazards for three vehicle weight classes (micro, mini, and small UAS), three vehicle configurations (fixed wing, multirotor, and helicopter), and three levels of operational complexity ranging from single UAS operation under VLOS in a remote/rural area to fully autonomous, multi-UAS operations under BVLOS conditions in suburban/urban/congested environments.

Proliferation of sUAS operations in the NAS gives rise to hazardous outcomes that are potentially catastrophic. Measures will be needed to manage the risk through the use of onboard technologies, procedural controls, and perhaps air traffic separation services to assure that sUAS operations can be incorporated into the airspace with an acceptable level of safety.

F. Future Research

Future research will consist of completing the safety risk management assessment for the full set of hazards at the vehicle, ground control station/infrastructure, operational, and UTM system levels. In follow-on risk analyses, we will also refine our estimates of the likelihood of occurrence of the identified hazard effects by performing a Failure Modes and Effects Analysis (FMEA) or Fault Tree analysis for specific UAS models with actual failure rates. In addition, the impact of the risk mitigation strategies identified above will be analyzed to determine an estimate of the residual risk of each hazard should the mitigations be implemented and shown to be effective. Methods for determining the effectiveness of mitigation systems, such as assessing performance through the use of hazards-based test scenarios, are also under development.[25]

IV. Probabilistic Model-Based Risk Assessment

An alternative risk assessment approach evaluated in this paper uses probabilistic modeling as the risk estimation vehicle given in Fig. 3. Similar to the Standard Safety Risk Management Assessment approach discussed in Section III, the probabilistic approach makes use of the current and future hazard identification processes to determine the causal/contributing factors, prominent hazards, and their outcomes. Previously identified mitigation strategies and their impacts are also incorporated into the model. Finally, the probabilistic approach considers the agreed upon TLS definitions for sUAS operations and compares them against estimated risk values obtained from the model, as highlighted in Section III. In order to demonstrate the approach, a simplified generic UAS accident model populated with arbitrary data was presented.

The probabilistic model outputs include (a) visualization of failure propagation or presence of single point failures obtained by testing various scenarios, (b) recommendations for the target aircraft component and system reliability values based on the selected TLS, and (c) estimated risk with and without the presence of mitigation factors. The next sections provide the probabilistic modeling approach (i.e. Bayesian belief networks or BBNs), modeling steps, and a preliminary mishap model used to demonstrate the approach.

A. Bayesian Belief Networks

A Bayesian Belief approach was used to model the complex UAS operational environment. Due to the large variety of aircraft configurations and dependence on ground and communication infrastructures, future UAS mishaps are expected to stem from a variety of system failures and external factors. The Bayesian method was found to be suitable to represent complex aviation safety accidents where multi-dependent causal factors are prominent.[26,27]

A BBN is a directed acyclic graph representation of a network-based framework. BBNs contain a set of discrete chance nodes which are connected via links designating their causal dependencies.[28,29] The discrete chance node probabilities are a function of its parent nodes' states, expressed with a conditional probability table (CPT). Each node's CPT includes all the possible combinations of its parent nodes. The probability calculation and propagation is performed using Bayes' theorem where the conditional probabilities can be obtained from both subject matter experts as well as historical data (see Ref. 26). The Bayesian approach is particularly useful in cases with high uncertainty where historical data is lacking given that both qualitative and quantitative data can be interpreted by the network simultaneously. The Hugin Expert software was used in this effort as it provides suitable flexibility and capabilities as highlighted in Ref. 30.

B. Modeling Steps

In order to develop the generic UAS mishap model, the first step was to collect and review military and civil UAS mishaps. A companion paper provides details on the mishap review as well as future sUAS use case evaluation.[10] Next, event sequence diagrams (ESDs) for mishaps conforming to the UTM operational framework, i.e. the aircraft weight is limited to 55 lbs. and the flights are below 400 ft. AGL were developed. The ESDs were then merged and generalized into a comprehensive probabilistic model representative of typical UTM use-cases (e.g. parcel delivery, agriculture, disaster monitoring, etc.). Next, the causal factors and model structure were evaluated and CPTs were populated by subject matter experts and estimated failure rates. Finally, the TLS values were implemented as evidence into the model to obtain the occurrence rates for the simulated system/component failures.

C. Model Details

The approach was demonstrated using the preliminary model, given in Figs. 5 and 6. In order to ease the demonstration, the object-oriented capability of Hugin software was employed. The object-oriented Bayesian network (OOBN) model allows encapsulation of major aircraft system details and their failures into a dedicated sub-model (Fig. 5) where the outputs are transferred to the top-level model (Fig. 6). The top-level model highlights the main hazards and links them to mishaps (or undesirable events) like mid-air collision (MAC), collision with obstacle, controlled flight into terrain (CFIT), loss-of-control (LOC), etc. It is important to note that the aim of the preliminary model is to represent a collection of aircraft weighing 55 lb or below, electric or internal combustion propulsion driven, fixed wing, or multi-rotor configuration. For that reason, the resulting model only demonstrates high-level aircraft systems. Also, given that this section is intended to assess the feasibility of the probabilistic approach, the model is not considered to be comprehensive. The next two sections provide model details.

1. Aircraft Systems Sub-Level Model

The generic aircraft system failure model includes four major aircraft system failures (propulsion, power, flight controls, and navigation), two inappropriate ground personnel actions (operator/pilot and maintenance related actions), two low-level hazards (inappropriate/impaired flight control input and aircraft state conducive to LOC) and finally, three main hazards (inappropriate guidance, loss-of-control, and loss of aircraft structural integrity). As stated previously, the links indicate a Bayesian inference where the parent node is a causal factor in the child node's failure probability. For instance, presence of wind, an improper flight control input, a propulsion system failure and/or a compromised aircraft structural integrity could all be causal factors to a loss-of-control conducive situation. Similarly, the aircraft is considered to be without proper navigation/guidance if the flight controls are operating unexpectedly, navigation hardware or software is inoperable and/or operator inappropriately programmed the aircraft waypoints.

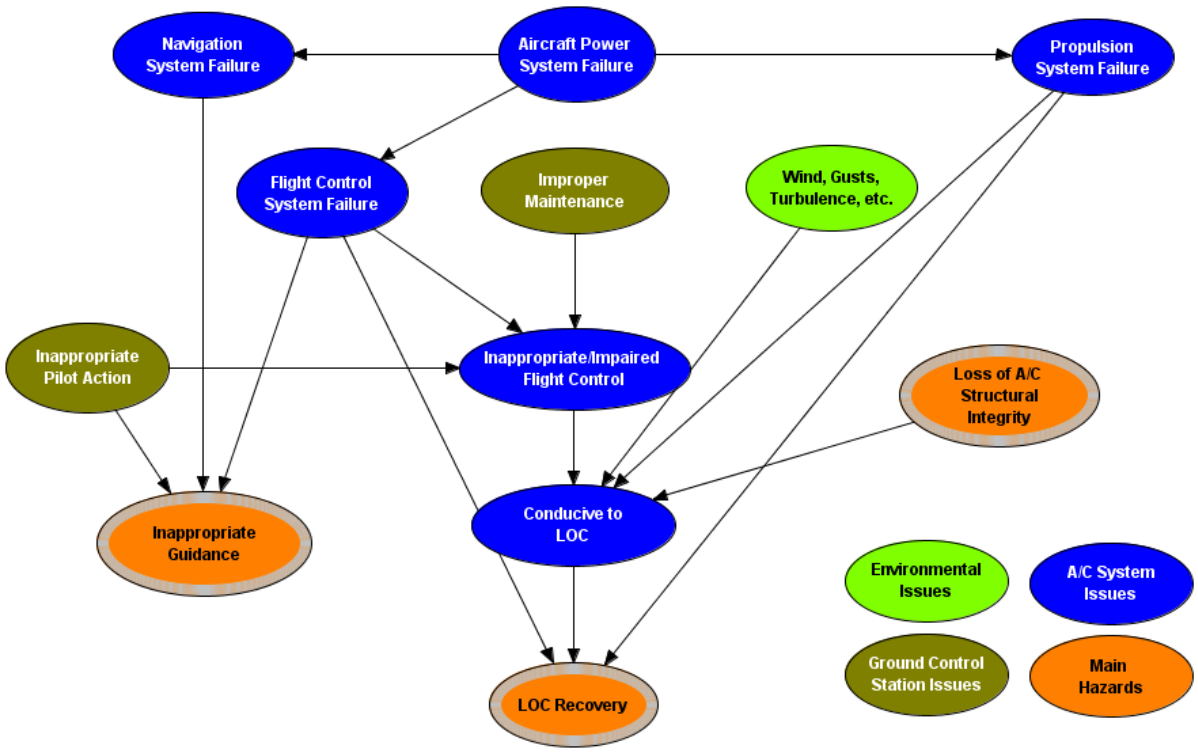


Figure 5. Aircraft Systems Sub-Level Model

2. *Top-level UAS Mishap Model*

As previously stated, the main hazards obtained from the sub-level model were imported to the top-level model using the object-oriented capability of Hugin software. At the top-level, the lost link node was introduced as another main hazard in addition to inappropriate guidance, loss of aircraft structural integrity, and loss-of-control hazards. The main outcomes envisioned in this model include mid-air-collision (MAC), collision with obstacle, controlled-flight into terrain (CFIT), uncontrolled crash following a LOC, continue mission, and return to base (RTB). Given that the model was designed to encompass the majority of flights performed under the conceptual UTM architecture, operational metrics such as presence of manned and unmanned air traffic, separation mechanism type, proximity to terrain and obstacles can be delineated to match the scenario that is being simulated. Based on its type, the separation mechanism failure can be affected by the status of the command and control link given in lost link node. For instance, presence of a lost link condition might render the in-flight separation service inoperable whereas it might not affect the on-board detect and avoid systems. In a similar fashion, the probability of a near mid-air collision (NMAC) situation is affected by the presence of UAS and manned aircraft in proximity (UTM operational metrics), inappropriate guidance, separation mechanism type and separation mechanism failure. Once the desired scenario variables are determined (e.g., low or high UAS operation density, presence or absence of manned aircraft in proximity, and separation mechanism type (procedural separation, in-flight separation services, or on-board detect and avoid systems)), the modeler can simulate failures and observe the NMAC and MAC rates. An example that illustrates the test scenarios is given in the next section.

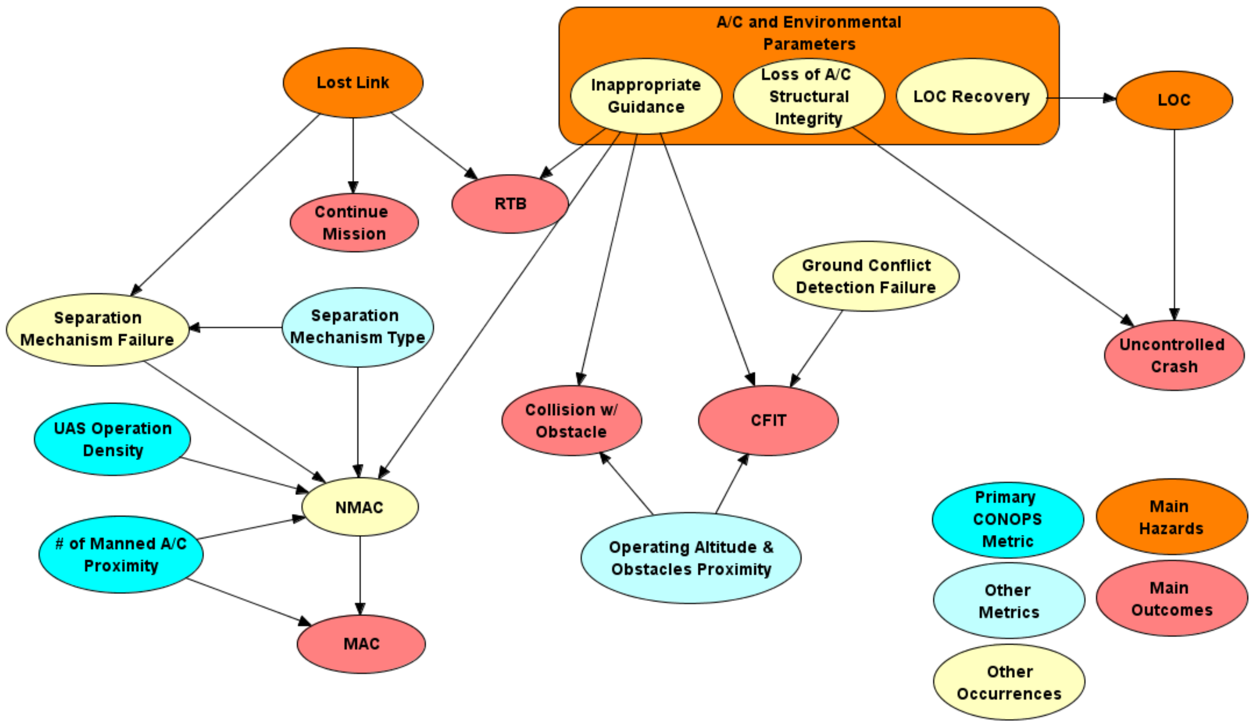


Figure 6. Top-Level UAS Mishap Model

D. Data Population and Test Scenario Visualization

1. Data Population

The model described above is populated with arbitrary and preliminary data in order to illustrate the concept. As previously stated, failures rates can be obtained via empirical data or by subject matter expert data solicitation sessions, and the software can populate CPTs by using discrete and continuous statistical distributions, numeric operators, and functions, based on available data. Given the multi-dependencies within the model, although individual component reliability levels can be estimated by empirical/historical values, the conditional failure probabilities need to be estimated by visiting each permutation (e.g., improper flight control input probability given the presence of inadequate pilot action, flight control system status as well as no evidence of improper maintenance, etc.).

The BBN model employs probability values for each discrete chance node and it outputs the probability of undesirable event states. In order to compare undesirable event occurrence to TLS failure rates and also to derive failure rates from system reliabilities, the relationship between failure rates and the probability of occurrence must be determined. As is frequently done in reliability analysis, our model assumed that failures follow a Poisson distribution with a constant average rate for the failure probabilities (or reliabilities)[31]. Consequently, the reliability function, $R(t)$ is given as an exponential distribution where λ is the failure rate and t is the length of time being considered (Eq. 1).

$$R(t) = e^{-\lambda t} \tag{1}$$

The timeframe was assumed to be one hour where failure rates are expressed as occurrences/hour. Using the expression above, undesirable event probabilities were converted to failure rates per hour which then were compared against the TLS values in Section IV.E.

2. Test Scenario Visualization

The populated model was used to simulate the effects of multiple failures and visualize failure propagation. In order to illustrate this capability, LOC probability of a battery powered aircraft was demonstrated in Fig. 7. Within this simulation, the model was executed to reproduce a black-out power state where the failure naturally propagated to propulsion and navigation systems, causing these systems to fail. Besides the power failure, it was also assumed that the flight was experiencing wind gusts; however, the pilot and maintenance actions were performed properly (simulated probabilities are marked with "e" which indicates the evidence was imposed on the node). Under such circumstances, the probability of unsuccessful LOC recovery was calculated to be 0.92415. Consequently, the probability of recovery, as interpreted as the LOC reliability, *R(t)*, was given as 0.07585, therefore resulting in λ = 2.56 occurrences /hour. On the other hand, without wind gusts, power system failure, or any other undesirable event occurrence (best case scenario), successful recovery from a LOC situation is calculated as 0.99334 (or $\lambda = 6.6\text{x}10^{-3}$ occurrences/hour). The unsuccessful recovery attempt from a LOC situation was transferred to the top-level model where it was defined as the causal factor for uncontrolled crash. Using the same approach, each causal factor can be individually or collectively set to fail and their effects on the hazardous events and outcomes can be simulated.

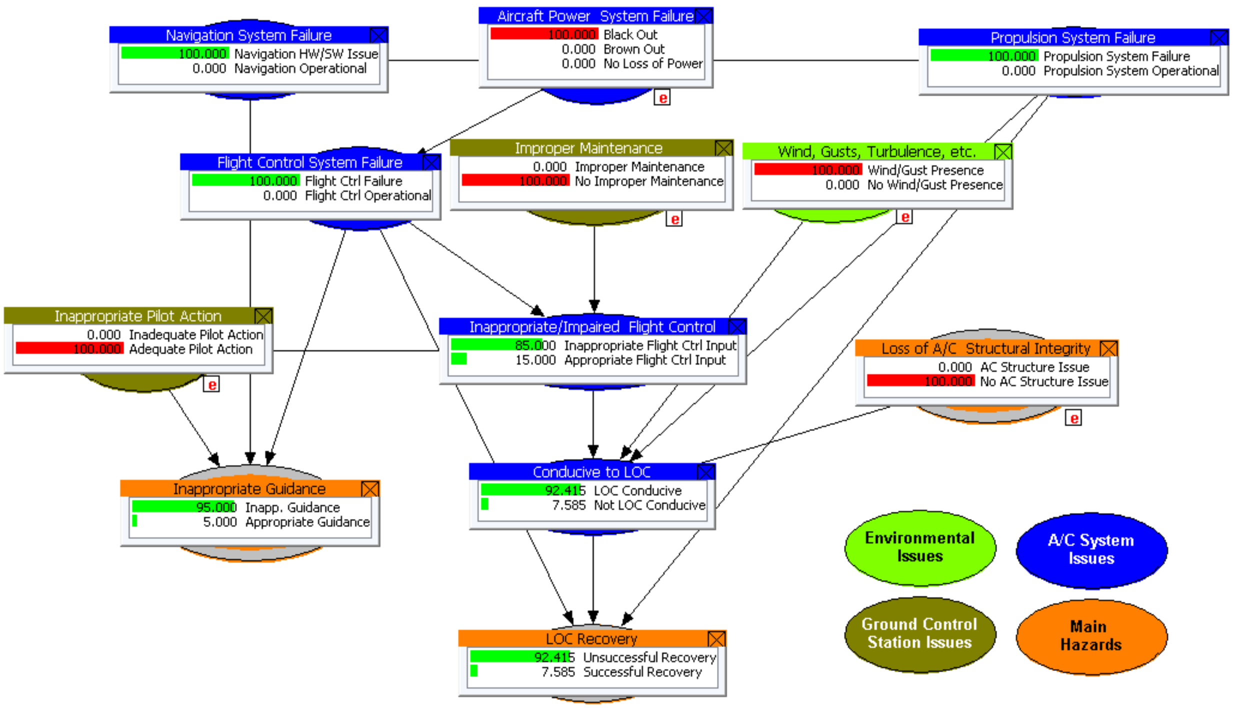


Figure 7. Black-Out Power Failure Simulation within Aircraft Systems Sub-Level Model

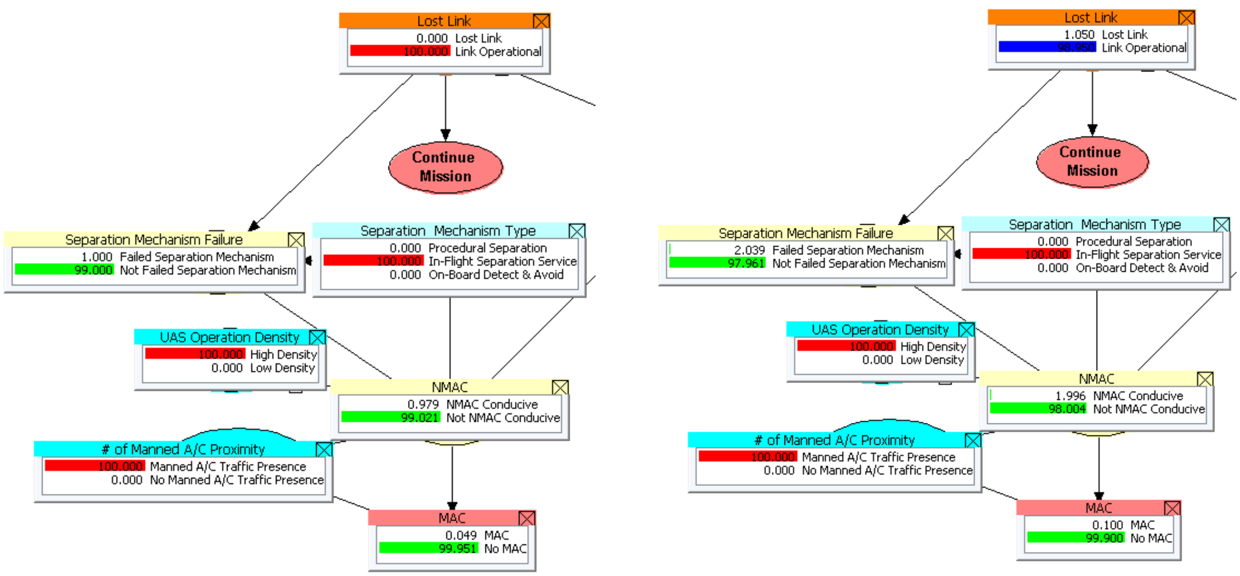
E. System Reliability Estimation using TLS and Mitigation Strategy Assessment

1. Target Level of Safety Approach

As discussed in the previous sections, the TLS concept is often employed to compare estimated risks against acceptable levels. In a similar fashion, the predetermined TLS values can also be used to help derive acceptable accident/incident rates for mishap types using the BBN model. In theory, it is possible to estimate component and system failure rates for the entire UAS fleet, however, recent SME meeting consensus indicated that acquiring data for heterogeneous operations (e.g. proximity to ground, manned and unmanned air traffic) for various types of aircraft (electric motors, internal combustion engines, number of propellers, fixed wing, multi-rotors and hybrid configurations) for a comprehensive model would prove to be challenging. Alternatively, a data collection and population effort for a specific aircraft configuration within a preset operational environment (e.g. parcel delivery in suburban setting using a COTS octocopter) would be more feasible.

The top-level UAS mishap model was used to demonstrate the TLS approach using BBN modeling, given in Fig. 8. A simulated case where fully operational command and control link (link operational state) yields to a MAC probability of 0.00049 (or around λ=5x10^{-4} occurrence/hour) considering an operational scenario with high UAS operation density and presence of manned aircraft traffic in proximity (Fig. 8a). In this scenario, the separation was provided by in-flight separation services which was assumed to be heavily dependent on an operational command and control link. Consequently, the lost link scenario causes the MAC probability to increase to 0.04894 (or around λ=5x10^{-2} occurrence/hour).

The TLS-based system reliability estimation is demonstrated in Fig. 8b where a hypothetical target MAC occurrence rate was selected as λ = 10^{-3} occurrences/hour. Using Eq. 1, the minimum MAC reliability is then calculated to be 0.999. Within the model, the MAC reliability is interpreted as the probability of not having a MAC accident by manually setting the No MAC probability to 0.999. Given the imposed MAC probability, the model provides the minimum required lost link reliability to be equal or higher than 0.98950. Solving Eq. 1 for λ, the maximum lost link failure rate is calculated to be 1.055x10^{-2} occurrence/hour. The simulated failure rate can be adopted as a baseline rate for the lost link reliability considering operational assumptions (i.e. separation mechanism or UAS and manned traffic presence). In summary, based on the adopted TLS values, failure rates of major aircraft systems can be estimated by matching the target failure rates to mishap occurrence rates using the BBN model.



a) MAC Probability given the link is operational

b) Minimum lost link probability mandated by TLS driven MAC occurrence rate

Fig 8. Simulated MAC vs Lost Link Probabilities

2. *Mitigation Strategy Assessment*

Due to their inexpensive and expandable nature, it may not be practical for UAS platforms to possess the same level of reliability as their manned counterparts. In cases where increasing the reliability levels is no longer economically feasible or desirable, strategic or tactical mitigations can be used to ensure the failure rates remain within the TLS values. In order to incorporate the effects of mitigations, decision node capability within Hugin software can be used. A decision node is employed to represent a choice made by the modeler. Unlike discrete chance nodes, decision nodes do not own their individual CPTs; instead, their initial states determine whether the decisions are implemented or not. The decision nodes alter the CPTs of the linked nodes, affecting their probabilities when the decision is executed. By observing individual or cumulative impacts of mitigations on the probability of mishaps, it is possible to rank mitigation alternatives with respect to their overall effectiveness. Mitigation effectiveness simulation can be executed in parallel with system and component failure rates estimation, allowing tradeoff analyses to be performed within the same model.

A sample mitigation simulating a detect and avoid capability was given in Fig. 9. The Sample Detect & Avoid Technology was applied to both NMAC and Collision w/ Obstacle nodes, lowering the occurrence probabilities of such undesirable when mitigation is applied. By modeling and simulating potential mitigation capabilities, it may be feasible to obtain the TLS values for undesirable events while evaluating and ranking available mitigations. Given that the sample model simulates mishap likelihoods, only mitigations aimed to decrease the likelihood of undesirable events can be represented. On the other hand, a modified model which considers the consequences of aforementioned mishaps can also be employed to evaluate the effectiveness of mitigations aimed towards decreasing the impact of mishaps (e.g., equipping the aircraft with a parachute to decrease the impact velocity in a LOC case to limit the kinetic energy, thus decreasing the risk of casualties on the ground).

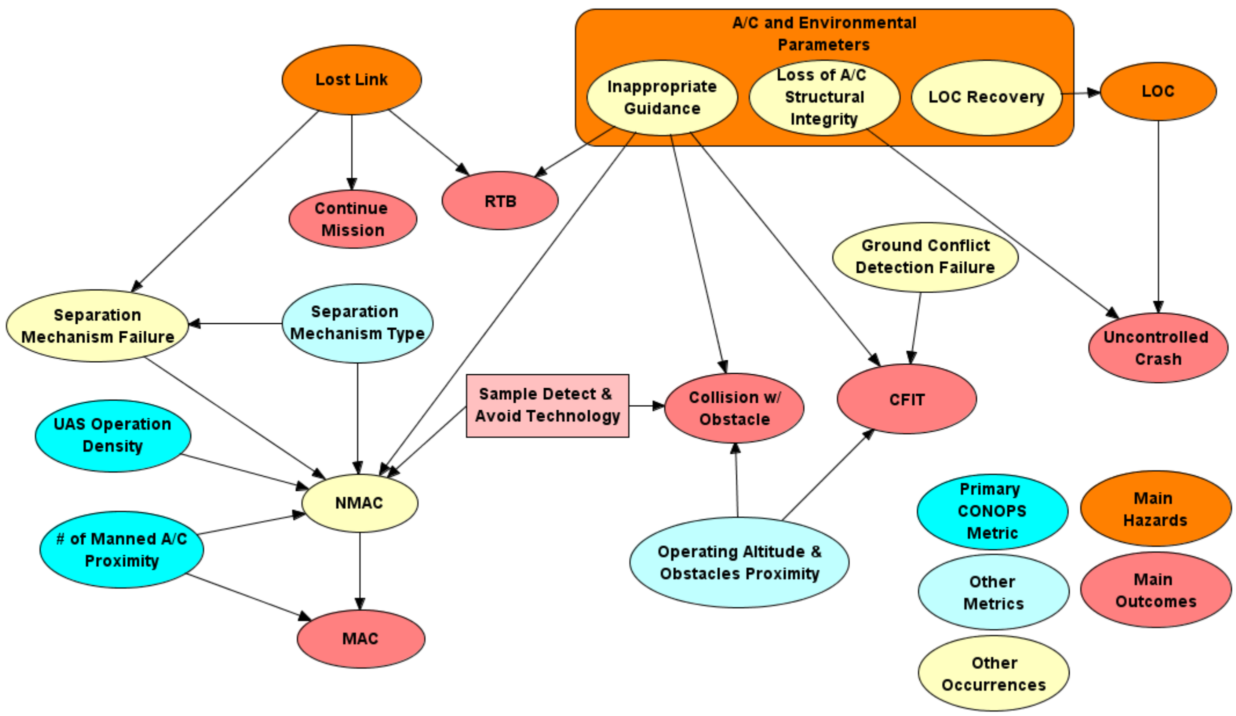


Figure 9. Top-Level UAS Mishap Model with Sample Mitigation

F. Discussions, Key Findings and Future Research

This goal of this section was to demonstrate the feasibility of employing generic or specific BBN models to test and visualize hazard scenarios, estimate component and system reliability values using TLS, and assess and rank the effectiveness of mitigation strategies and scenarios. Using a simplified generic UAS mishap model, propagation of failures, scenario testing and target system failure rates were demonstrated. Although BBN model development might be perceived as a straightforward process, population of individual failure rates and conditional failure probabilities for complex models was proven to be challenging. Future research efforts will include the development of a UAS-specific BBN model that will be populated with a series of SME sessions and empirical data. Additionally, the assumption of reliability function representation with exponential expression will be revised to ensure suitable failure representation of individual components.

V. Conclusion

This paper presented the results of a preliminary safety risk assessment of small unmanned aircraft systems. Two approaches were used. The first approach followed a qualitative safety risk management process in which an analysis is conducted to identify operational hazards, along with their possible causes and existing safety controls, associated with proposed sUAS operational applications and use cases. Sample results were discussed for one of the identified hazards, aircraft loss of control. In addition, a numerical risk assessment showing data on sUAS failure rates and an example result for a quadrotor striking a person on the ground is presented. The second approach used a probabilistic model-based risk estimation methodology. Bayesian Belief Networks were used to model the complex UAS operational environment. Using a simplified generic UAS mishap model, propagation of failures, scenario testing, and target system failure rates were demonstrated.

Future work will include a full numerical estimation of risks for additional hazards in our hazards set using the standard risk assessment approach, which may require the development of a software tool to assist in the calculations. We will also assess residual risk based on the use of mitigation strategies, which will require an assessment of their effectiveness using realistic test scenarios. The evaluations will be accomplished using sUAS simulations and flight testing. The probabilistic model will also be exercised, refined, and applied in assessing multiple hazard effects with and without mitigation systems. A more thorough assessment of TLS will be performed both in terms of risk as well as relative to the identification of safety recommendations and requirements (e.g., system reliability and resilience).

Appendix A: Combined Hazards Set

This appendix provides the full set of Combined Hazards developed at the vehicle level in Ref. [10]. For the preliminary risk analysis of this paper, the first seven hazards were selected for analysis. Future risk analyses will consider the full set below, as well as a complete set of defined hazards at all operational levels (see Fig. 2).

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-1	Aircraft Loss of Control (LOC)	Any / All Use Cases Associated with: Remote / Rural Location (Includes Precision Agriculture, Border Patrol, Wildfire Monitoring & Control, Package Delivery, etc.)	• Single UAS Manually Controlled by Remote Pilot under VLOS • Low-Density Airspace	• Vehicle Failures / Impairment • Control System Failures / Malfunctions / Inadequacy • Propulsion System Failure / Malfunction • Weather (Includes Rain, Snow / Icing, Thunderstorms, etc.) • Wind / Wind Shear / Turbulence (Includes Boundary Layer Effects) • Vehicle Upset Condition / Damage • Pilot Error • Power Loss / Fuel Exhaustion • Electromagnetic Interference (EMI) • Unsuccessful Launch • Flight Control System Design / Validation Errors / Inadequacy • Flight Control System Software Implementation / Verification Error / Inadequacy • Unexpected Obstacle Encounter Results in Unstable / Aggressive Avoidance Maneuver • Bird Strike • Others	• Undesired Flight Trajectory that is Difficult to Predict • Unpredictable / Unstable Control Response • Uncontrolled Descent	• Vehicle Exits Assigned Geofence • Uncontrolled Descent / Landing • Uncontrolled Descent into Terrain / Water • Vehicle Damage / Break-Up	• Mid-Air Collision with UAS • Mid-Air Collision with Manned Aircraft • Crash into Building / Obstacle Injures People • Crash Debris Injures People on Ground • Damage to Ground Asset Causes Fire
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Package Delivery, Traffic Monitoring, Infrastructure Inspection, etc.)	• Single UAS, Semi-Autonomous Control, BVLOS • Moderate- / High-Density Airspace	• All Hazards Listed Above • Payload / CG Shift / Instability • Inadequate Resilience in Flight Control System to Key LOC Hazards (Including Failures, Wind / Weather, etc.) • Unexpected Obstacle Encounter Results in Unstable / Aggressive Avoidance Maneuver • Boundary Layer Wind Effect • Vehicle Instability Resulting from Attempted Retrieval of Objects of Unknown size/weight • Vehicle Instability Resulting from Failure/Malfunction of Object Retrieval System • Launch/Landing Instability on Water-Based Platform • Propulsion or Vision Systems Failure / Inadequacy under Harsh Conditions (Fire, Smoke, Ash, Smog, Salty Sea Air, etc.)	• Above Results • Potential for LOC Involving Multiple UAS under Common Causal Conditions (e.g., Unexpected Wind / Weather)	• Above Impacts Involving Multiple (Potentially Many) UAS • MAC with One or More Manned Aircraft • One or More Collisions with Critical Infrastructure	• Above Outcomes on Potentially Large Scale • People on the Ground are Injured / Killed in Potentially Large Region or Multiple Regions • People in One or More Manned Aircraft are Injured / Killed • One or More Critical Infrastructure is Damage / Destroyed
		Any / All Use Cases Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• All Hazards Listed Above • Vehicle Damage (e.g., Lightning strike during long-duration missions, Damage from Explosion / Fire during Emergency Response, Radiation Exposure from HALE operations over urban areas, etc.) • Harsh Environmental Conditions (e.g., Extreme Temperatures, etc.) • Cascading Factors Involving Multi-UAS Operations • Unexpected Battery Depletion	• Above Results • Potential for LOC Involving Many UAS (Particularly from Design / Validation Inadequacy that Affects Multiple UAS and Multi-UAS Operations)		

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-2	Aircraft Fly-Away / Geofence Non-Conformance	Any / All Use Cases Associated with: Remote / Rural Location (Includes Precision Agriculture, Border Patrol, Wildfire Monitoring & Control, Package Delivery, etc.)	• Single UAS Manually Controlled by Remote Pilot under VLOS • Low-Density Airspace	• Loss of Communication / Control Link • Erroneous Way Points • GPS Failure / Errors • Autopilot Error / Malfunction • Pilot Error	• Inability to Control Aircraft from Ground • Inability to Monitor Aircraft Position • Inability to Initiate Flight Termination from Ground	• UAS Exits Assigned Geofence • Aircraft LOC	• Mid-Air Collision with UAS • Mid-Air Collision with Manned Aircraft • Crash into Building / Obstacle Injures People • Crash Debris Injures People on Ground
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Package Delivery, Traffic Monitoring, Infrastructure Inspection, etc.)	• Single UAS, Semi-Autonomous Control, BVLOS • Moderate- / High-Density Airspace	• GPS Signal Loss / Error • Network Unavailability • Onboard GPS System Failure / Malfunction • Lack of Navigational Redundancy • Jamming / Spoofing of GPS and/or V-V Signals • Erroneous Way Points • Error in Autonomous Mission Planner (Includes V&V Inadequacy)	• Above Results • Potential for Widespread Collisions under Common Causal Conditions (e.g., Network Loss)	• One or More UAS Exit Assigned Geofence • One or More UAS Enter Aircraft LOC Condition	• Potential for Above Outcomes on Larger Scale Involving Multiple UAS
		Any / All Use Cases Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully- Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• All of the Above • Loss of Navigation Capability by One or More UAS • Inadequate Design / Validation and/or Implementation / Verification of Coordinated Multi-UAS Operations • Communication Interference Among Multi-UAS Operators (e.g., EMI and/or Lack of Frequency Separation) • Inadequate Contingency Management	• Above Results • Potential for Widespread Results Involving Many UAS (Particularly from Design / Validation Inadequacy that Affects Multiple UAS and Multi-UAS Operations)	• Potentially Many UAS Exit Assigned Geofence • Potentially Many UAS Enter Aircraft LOC Condition	• Potential for Above Widespread Outcomes on Large Scale Involving Multiple UAS

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-3	Lost Communication / Control Link	Any / All Use Cases Associated with: Remote / Rural Location (Includes Precision Agriculture, Border Patrol, Wildfire Monitoring & Control, Package Delivery, etc.)	• Single UAS Manually Controlled by Remote Pilot under VLOS • Low-Density Airspace	• EMI at Vehicle • Signal Obscurence • Frequency / BW Overlap • Failure in GCS (e.g., Power Failure, etc.)	• Inability to Control Aircraft from Ground • Inability to Monitor Aircraft Position • Inability to Initiate Flight Termination from Ground • Return to Base	• UAS Exits Assigned Geofence • Aircraft Loss of Control (LOC) • Controlled Flight into Terrain / Obstacle	• Mid-Air Collision with UAS • Mid-Air Collision with Manned Aircraft • Crash into Building / Obstacle Injures People • Crash Debris Injures People on Ground
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Package Delivery, Traffic Monitoring, Infrastructure Inspection, etc.)	• Single UAS, Semi-Autonomous Control, BVLOS • Moderate- / High-Density Airspace	• GPS Drop-Outs in Urban Environments • EMI Weapon Targeting One or More UAS • Signal Jamming / Spoofing • Frequency / BW Block • Network Unavailability	• Inability to Fly Desired Trajectory • Inability to Remotely Initiate Flight Termination • Potential for Widespread Collisions under Common Causal Conditions (e.g., Network Loss, Widespread Jamming)	• One or More UAS Exit Assigned Geofence • Aircraft Loss of Control (LOC) Involving One or More UAS • Controlled Flight into Terrain / Obstacle by One or More UAS	• Mid-Air Collision with One or More UAS • MAC with Manned Aircraft by One or More UAS • One or More UAS Collisions with One or More Buildings • Crash Debris Injures People on Ground
		Any / All Use Cases Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• All of the Above • Communication Interference Among Multi-UAS Operators (e.g., EMI and/or Lack of Frequency Separation) • Others	• Above Results • Potential for Widespread Results Involving Many UAS (Particularly from Design / Validation Inadequacy that Affects Multiple UAS and Multi-UAS Operations)	• Potentially Many UAS Exit Assigned Geofence • Aircraft Loss of Control (LOC) Involving Potentiallu Many UAS • Controlled Flight into Terrain / Obstacle by Potentially ManyUAS	• Potential for Above Widespread Outcomes on Large Scale Involving Multiple UAS

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-4	Loss of Navigation Capability	Any / All Use Cases Associated with: Remote / Rural Location (Includes Precision Agriculture, Border Patrol, Wildfire Monitoring & Control, Package Delivery, etc.)	• Single UAS Manually Controlled by Remote Pilot under VLOS • Low-Density Airspace	• Onboard Navigation System Failure / Malfunction • Loss of / Erroneous GPS Signal • Ground Station Set-Up Error	• Inability to Fly Desired Trajectory • Intentional Grounding	• UAS Exits Assigned Geofence	• Mid-Air Collision with UAS • Mid-Air Collision with Manned Aircraft • Crash into Building / Obstacle Injures People • Crash Debris Injures People on Ground
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Package Delivery, Traffic Monitoring, Infrastructure Inspection, etc.)	• Single UAS, Semi-Autonomous Control, BVLOS • Moderate- / High-Density Airspace	• Hostile Takeover and Control of UAS • GPS / ADS-B Signal Inaccuracy / Jamming / Spoofing • Network Unavailability • Vision System Inadequacy under Low-Visibility Conditions • Inadequate Perception of Visual Scene by Vision System	• Above Results • UAS Location is Inaccurate or Cannot be Determined • Potential for Widespread Collisions under Common Causal Conditions (e.g., GPS Signal or Network Loss)	• One or More UAS Leaves Assigned Geofence • Safe Separation Cannot be Maintained	• MAC(s) Among One or More UAS • MAC(s) with Manned Aircraft • Collision(s) with Terrain, Obstacle(s), Building(s) • Crash Debris Injures People on Ground
		Any / All Use Cases Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• All of the Above • Autonomous Navigation System Error / Failure / Inadequacy • Lack of Resilience under Off-Nominal Conditions • Error Propagation Across Multi-UAS Autonomous Systems • Others	• Above Results • Potential for Widespread Collisions under Common Causal Conditions & Error Propagation Associated with Multi-UAS Operations	• Potentially Many UAS Exit Assigned Geofence • Potential for Widespread Collisions	• Potential for Above Widespread Outcomes on Large Scale Involving Multiple UAS
VH-5	Unsuccessful Landing	Any / All Use Cases Single UAS Manually Controlled by Remote Pilot under VLOS Operations	Within Runway Safety Area	• Unstable Approach • Remote Pilot Error	• Abnormal Runway Contact • Crash on Landing	• Vehicle Damage / Break-Up	• Post-Crash Fire that Injures Ground Crew
			Outside Runway Safety Area				• Crash Debris Injures People on Ground

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-6	Unintentional / Unsuccessful Flight Termination	Any / All Use Cases Associated with: Remote / Rural Location (Includes Precision Agriculture, Border Patrol, Wildfire Monitoring & Control, Package Delivery, etc.)	• Single UAS Manually Controlled by Remote Pilot under VLOS • Low-Density Airspace	• Pilot Error in Either Initiating or Executing Flight Termination • Flight Termination System Error / Failure / Malfunction • Unexpected Wind / Weather Negatively Impacts Flight Termination • Failure of Command Link from Operator to Initiate Flight Termination	• UAS lands or has a forced crash in an unsafe location	• UAS Damage / Break-Up	• Post-Crash Fire that Threatens Wildlife & Environment
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Package Delivery, Traffic Monitoring, Infrastructure Inspection, etc.)	• Single UAS, Semi-Autonomous Control, BVLOS • Moderate- / High-Density Airspace	• Inadequate Database for or RT Identification of Safe Landing Zone • Vision System Inadequacy under Low-Visibility Conditions • Inadequate Perception of Visual Scene by Vision System • Failure of Command Link from Operator or Network to Initiate Flight Termination • Failure / Inadequacy of the Onboard Flight Termination System	• One or more UAS land or have a forced crash in one or more unsafe locations	• Damage / Break-Up of One or More UAS	• UAS injures people on ground • UAS crashes into ground vehicle • UAS causes accident involving ground vehicles • UAS Collides with Infrastructure (Building, Bridge, Power Lines / Sub-Station, etc.)
		Any / All Use Cases Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully- Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• All of the Above • Failure / Error / Inadequacy of Flight Termination System for Multi-UAS and Coordinated Multi-UAS Operations	• Potentially many UAS land or have a forced crash in multiple unsafe locations	• Damage / Break-Up of Potentially Many UAS	• Multiple UAS injure people on ground • One or more UAS crash into ground vehicle • One or more UAS cause accident involving ground vehicles • Multiple UAS Collide with Infrastructure (Building, Bridge, Power Lines / Sub-Station, etc.)

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-7	Failure / Inability to Avoid Collision with Terrain and/or Fixed / Moving Obstacle	Any / All Use Cases Associated with: Remote / Rural Location (Includes Precision Agriculture, Border Patrol, Wildfire Monitoring & Control, Package Delivery, etc.)	• Single UAS Manually Controlled by Remote Pilot under VLOS • Low-Density Airspace	• Pilot Error / Poor Judgment • Wind / Weather that Results in Abnormal Flight Trajectory • Erroneous Way Points that Create Conflict with Obstacle • Inaccurate GPS Signal • Inadequate Navigation / Tracking	• Collision with Building • Collision with Power Lines • Collision with Ground Vehicle	• UAS Break-Up	• Crash Debris Injures People on Ground • UAS / Crash Debris Causes Ground Vehicle Accident on Highway • Post-Crash Fire that Damages Building and/or Injures People Inside the Building • Post-Crash Fire that Damages Power System & Environment
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Package Delivery, Traffic Monitoring, Infrastructure Inspection, etc.)	• Single UAS, Semi-Autonomous Control, BVLOS • Moderate- / High-Density Airspace	• Above • Inadequate / Lack of Sense/Detect and Avoid (SAA/DAA) Capability • Inadequate Design / Validation or Failure of SAA / DAA System • Vision System Failure / Inadequacy in Low Visibility Conditions • Missed Detection of Obstacle • Inadequate / Erroneous / Incomplete Terrain Database • Inadequate / Ineffective Sensor System for Detection of Small / Thin Obstacles (e.g., Power Lines) • Inadequate Resilience to Key Hazards (e.g., component failures, external disturbances) • Launch/Landing Instability on Water-Based Platform • Propulsion or Vision Systems Failure / Inadequacy under Harsh Conditions (Fire, Smoke, Ash, Smog, Salty Sea Air, etc.)	• Collision with Infrastructure (Building, Bridge, Power Lines / Sub-Station, etc.) or Terrain Features • Collision with Ground Vehicle • Mid-Air Collision with UAS • Mid-Air Collision with Manned Aircraft • Potential for Widespread Collisions under Common Causal Conditions (e.g., Poor Visibility)	• Break-Up of One or More UAS • Damage to Air / Ground Vehicle	• UAV Collides with High-Voltage Power Lines and Causes a Fire / Explosion • MACs with One or More UAS • Crash by One or More UAS into Building / Obstacle and Injures People • MAC with Manned Aircraft by One or More UAS • Crash Debris Injures People on Ground • Damage to ground asset causes fire • UAS / Crash Debris Causes Ground Vehicle Accident on Highway • UAS Damages Manned Aircraft & Injures People on Board • UAS Damages Manned Aircraft & Results in Aircraft Accident
		Any / All Use Cases Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace		• Above Results • Potential for Widespread Collisions under Common Causal Conditions & Error Propagation Associated with Multi-UAS Operations	• Break-Up of Multiple UAS • Damage to One of More Air / Ground Vehicles	• Potential for Widespread Collisions involving Multiple UAS

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-8	Hostile Remote Takeover and Control of UAS	Any / All Use Cases Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• Lack of Data / Cyber Security by Operator or within UTM System • Increasing Level of Sophistication of Terrorist Threat	• UAS is no longer under operator control • Potential for Simultaneous Takeover of Multiple UAS	• One or More UAS Leaves Assigned Geofence	• One or More UAS is Intentionally Crashed into Manned Aircraft • One or More UAS is Intentionally Crashed into Vital Infrastructure
VH-9	Rogue / Noncompliant UAS	Any / All Use Cases Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• Inability by UTM System to Stop Rogue / Noncompliant Operation(s) of UAS • Inability to Detect / Contain Rogue UAS • Ineffective Methods for Detecting / Containing Rogue UAS • Unsuccessful Detection / Containment of Rogue UAS	• One or More UAS is Not Operating within UTM System • One or More UAS Does Not Operate within an Assigned Geofence • One or More UAS Flight Plan is Unknown to Other UAS Operating with UTM System • Potential for Large-Scale Implications Involving Multiple Rogue UAS	• One or More UAS is Used to Interfere with Other UAS Missions (e.g., Search & Rescue) • One or More UAS is Used to Terrorize / Injure / Kill People on the Ground or to Gather Intelligence for Future Use in Terrorist Activities • One or More UAS is Used to Deliver Chemical / Biological Toxins • Aircraft loss of control • Destruction of Rogue UAS • Destruction of Innocent UAS in the same area	• People on the Ground are Poisoned, Injured, or Killed in Potentially Large Region or Multiple Regions • People in One or More Manned Aircraft are Injured / Killed • UAS causes accident involving ground vehicles • Negative Impact to Wildlife and Environment from UAS crash or Rogue UAS mission
VH-10	Rogue / Noncompliant UAS (Weaponized)		• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace			• One or More UAS is Used as a Sniper • One or More UAS is Used as a Weapon of Mass Destruction (WMD)	• People on the Ground are Injured / Killed in Potentially Large Region or Multiple Regions • People in One or More Manned Aircraft are Injured / Killed • One or More Critical Infrastructure is Destroyed

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-11	Hostile Ground-Based Attack of UAS (e.g., Using High-Powered Rifle, UAS Counter Measure Devices, etc.)	Any / All Use Cases Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully- Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• Any / All Use Cases • Suburban / Urban • Moderate- / High-Density Operations • Inability to Prevent Such Attacks by FAA, UTM System, Law Enforcement	• Aircraft LOC Resulting from Vehicle Damage • Inflight UAS Breakup • Potential for Large-Scale Implications Involving Multiple UAS In Single or Multiple Regions	• Inability to Fly Desired Trajectory • UAS Exits Assigned Geofence	• Mid-Air Collision with One or More UAS • MAC with Manned Aircraft by One or More UAS • One or More UAS Collisions with One or More Buildings • Crash Debris Injures People on Ground
VH-12	Unintentional / Erroneous Discharge of Weapons, Explosives, Chemicals, etc.	Any / All Use Cases Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully- Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• Destruction of Vehicle Carrying Dangerous Cargo / Weapons (e.g., Toxic Substances / Chemicals, Explosives, etc.) • Failure of Delivery / Discharge System • Leak in Chemical Containment System • Unsuccessful Containment / Capture of Rogue UAS	• Stray Bullets • Explosion On / Near UAS • Release of Chemical Toxins	• UAS Damage / Break-Up • Damage to Other UAS • Damage to Nearby Manned Aircraft • Damage to Nearby Infrastructure	• Stray Bullets Injure / Kill People on Ground • Crash Debris Injures / Kills People on Ground • People on Manned Aircraft are Inured / Killed • Cascading Effects of Damaged Vehicles or Injured Persons on Roadways Leading to More Injury or Damage • People / Wildlife / Plant Life Harmed by Release of Toxic Chemicals

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-13	Erroneous Autonomous Decisions / Actions by UAS Compromise Vehicle / Operational Safety	Any / All Use Cases Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• Inadequate Sensor Integrity Management for Critical Decision-Making by the System • Error Propagation Across Vehicle Autonomous Systems and Systems of Systems • Inadequate Resilience under Off-Nominal Conditions • Inadequate System Validation & Software Verification	• Unreliable / Unexpected Actions by One or More UAS under Nominal or Off-Nominal Conditions • UAV Makes Faulty Decision that Results in Unsafe Flight / Mission	• UAS Exits Assigned Geofence • Aircraft Loss of Control (LOC) • Collision with Infrastructure (Building, Bridge, Power Lines / Sub-Station, etc.) or Terrain Features • Potential Impacts to Multiple UAS in Collaborative Mission	• Mid-Air Collision with One or More UAS • MAC with Manned Aircraft by One or More UAS • One or More UAS Collisions with One or More Buildings • Crash Debris Injures People on Ground • People in One or More Manned Aircraft are Injured / Killed
VH-14	Cascading Failures in Multi-UAS and Collaborative Missions	Any / All Use Cases Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• Lack of Resilience in One or More UAS under Off-Nominal Conditions • Failure of Single Vehicle System that Affects Multiple UAS • Communication Interference / EMI Across Multi-UAS Operations • Error / Failure of Collaborative Control & Decision-Making • Inadequate Real-Time Safety Monitoring (Includes Autonomous & Human Operator and Inadequate Interfaces for Human-Automation Teaming) • Inadequate System Validation and/or Software Verification with or Across Multiple Interconnected Systems • Loss of Navigation Capability by One or More UAS	• Aircraft LOC Involving Multiple (Potentially Many) UAS • Loss of Separation Involving Multiple (Potentially Many) UAS • One or More UAS Exit(s) Assigned Geofence	• In-Flight UAS Damage / Breakup Involving Multiple (Potentially Many) UAS • MAC with One or More Manned Aircraft • One or More Collisions with Critical Infrastructure • MAC between potentially multiple UAS	• People on the Ground are Injured / Killed in Potentially Large Region or Multiple Regions • People in One or More Manned Aircraft are Injured / Killed • One or More Critical Infrastructure is Damage / Destroyed • Environment is Compromised by Crash Debris (e.g., Fuel Spill)

Appendix B: Summary of Preliminary Risk Assessment Results

Preliminary Risk Assessment Summary – Aircraft Loss of Control

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-1 **Aircraft Loss of Control** Operating Environment: • Remote/Rural Location • Low-Density Operations • Single UAS • Manual Control by Pilot • VLOS / BVLOS	PE-1: Undesired flight trajectory and/or uncontrolled descent could cause the aircraft to potentially collide with another UAS or a manned aircraft operating in the area. PE-2: Undesired flight trajectory and/or uncontrolled descent could result in striking a person on the ground causing injury or fatality. PE-3: Undesired flight trajectory and/or uncontrolled descent could cause the aircraft to potentially crash into a building/obstacle resulting in secondary injury from UAS debris or building damage.	Micro UAS (0 < W≤ 4.4 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
		Mini UAS (4.4 < W ≤ 20 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
		Small UAS (20 < W ≤ 55 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Extremely Remote

Preliminary Risk Assessment Summary – Aircraft Loss of Control (continued)

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-1 **Aircraft Loss of Control** Operating Environment: • Suburban / Urban Location • Moderate-to-High-Density Operations • Single- or Multi-UAS Operations • Semi-Autonomous Control • BVLOS	PE-1. Potential for LOC involving multiple UAS under common causal conditions (e.g., unexpected wind / weather) resulting in midair collision with other UAS/manned aircraft and potentially one or more injuries/fatalities. PE-2: Undesired flight trajectory and/or uncontrolled descent of multiple UAS could result in striking multiple persons on the ground causing injury or fatality. PE-3. Undesired flight trajectory and/or uncontrolled descent by multiple UAS could cause multiple crashes into a building/obstacle resulting in secondary injury from UAS debris or building damage.	Micro UAS (0 < W≤ 4.4 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Mini UAS (4.4 < W ≤ 20 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Small UAS (20 < W ≤ 55 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote

Preliminary Risk Assessment Summary – Aircraft Loss of Control (continued)

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-1 **Aircraft Loss of Control** Operating Environment: • Suburban / Urban / Congested Locations • Moderate-to-High-Density Operations • Single- or Multi-UAS Operations • Semi- or Fully-Autonomous Control • BVLOS	PE-1. Undesired flight trajectory could cause collision with other UAS or manned aircraft and an uncontrolled descent or landing could cause serious injury to many persons on the ground and possible fatalities. PE-2: Undesired flight trajectory and/or uncontrolled descent involving multiple UAS could result in widespread injuries / fatalities to persons on the ground. PE-3. Potential for LOC involving multiple UAS under common causal conditions or from design / validation inadequacy that affects multiple UAS and multi-UAS operations could cause multiple UAS to crash into a one or more buildings /obstacles resulting in widespread secondary injury from UAS debris and / or building damage.	Micro UAS ($0 < W \leq 4.4$ lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Mini UAS ($4.4 < W \leq 20$ lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Small UAS ($20 < W \leq 55$ lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote

Preliminary Risk Assessment Summary – Aircraft Flyaway

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-2 **Aircraft Flyaway** Operating Environment: • Remote/Rural Location • Low-Density Operations • Single UAS • Manual Control by Pilot • VLOS / BVLOS	PE-1: Inability to control the aircraft from the ground and/or monitor aircraft position could cause the aircraft to potentially collide with another UAS or a manned aircraft operating in the area. PE-2: Inability to control the aircraft from the ground and/or monitor aircraft position could result in striking a person on the ground causing injury or fatality. PE-3: Inability to control the aircraft from the ground and/or monitor aircraft position could cause the aircraft to potentially crash into a building/obstacle resulting in secondary injury from UAS debris or building damage.	Micro UAS ($0 < W \leq 4.4$ lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
		Mini UAS ($4.4 < W \leq 20$ lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
		Small UAS ($20 < W \leq 55$ lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Extremely Remote

Preliminary Risk Assessment Summary – Aircraft Flyaway (continued)

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-2 **Aircraft Flyaway** Operating Environment: • Suburban / Urban Location • Moderate-to-High-Density Operations • Single- or Multi-UAS Operations • Semi-Autonomous Control • BVLOS	PE-1. Potential for LOC involving multiple UAS under common causal conditions (e.g., network loss) resulting in midair collision with other UAS/manned aircraft and potentially one or more injuries/fatalities. PE-2: Inability to control the aircraft from the ground and/or monitor aircraft position could result in striking multiple persons on the ground causing injury or fatality. PE-3. Inability to control one or several aircraft from the ground and/or monitor aircraft position could cause multiple crashes into a building/obstacle resulting in secondary injury from UAS debris or building damage	Micro UAS (0 < W≤ 4.4 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Mini UAS (4.4 < W ≤ 20 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Small UAS (20 < W ≤ 55 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote

Preliminary Risk Assessment Summary – Aircraft Flyaway (continued)

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-2 **Aircraft Flyaway** Operating Environment: • Suburban / Urban / Congested Locations • Moderate-to-High-Density Operations • Single- or Multi-UAS Operations • Semi- or Fully-Autonomous Control • BVLOS	PE-1: Inability to control the aircraft from the ground and/or monitor aircraft position could potentially result in multiple collisions with other UAS or a manned aircraft operating in the area. PE-2: Inability to control the aircraft from the ground and/or monitor aircraft position involving multiple UAS could result in widespread injuries / fatalities to persons on the ground. PE-3. Potential for flyaway involving multiple UAS under common causal conditions or from design / validation inadequacy that affects multiple UAS and multi-UAS operations could cause multiple UAS to crash into a one or more buildings /obstacles resulting in widespread secondary injury from UAS debris and/or building damage.	Micro UAS (0 < W≤ 4.4 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Mini UAS (4.4 < W ≤ 20 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Small UAS (20 < W ≤ 55 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote

Preliminary Risk Assessment Summary – Aircraft Lost Communication / Control Link

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-3 Aircraft Lost Communication / Control Link Operating Environment: • Remote/Rural Location • Low-Density Operations • Single UAS • Manual Control by Pilot • VLOS / BVLOS	PE-1: Inability to control the aircraft from the ground, monitor aircraft position, and/or initiate flight termination from the ground leads to a loss of control and a potential collision with another UAS or a manned aircraft operating in the area. PE-2: Inability to control the aircraft from the ground, monitor aircraft position, and/or initiate flight termination from the ground could result in striking a person on the ground causing injury or fatality. PE-3: Inability to control the aircraft from the ground, monitor aircraft position, and/or initiate flight termination from the ground leads to a loss of control causing the aircraft to potentially crash into a building/obstacle and resulting in secondary injury from UAS debris or building damage.	Micro UAS (0 < W≤ 4.4 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
		Mini UAS (4.4 < W ≤ 20 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
		Small UAS (20 < W ≤ 55 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Extremely Remote

Preliminary Risk Assessment Summary – Aircraft Lost Communication / Control Link (continued)

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-3 Aircraft Lost Communication / Control Link Operating Environment: • Suburban / Urban Location • Moderate-to-High-Density Operations • Single- or Multi-UAS Operations • Semi-Autonomous Control • BVLOS	PE-1: Inability to control the aircraft from the ground, monitor aircraft position, and/or initiate flight termination from the ground creates the potential for widespread collisions with another UAS or a manned aircraft operating in the area under common causal conditions (e.g., network loss, widespread jamming) PE-2: Inability to control the aircraft from the ground, monitor aircraft position, and/or initiate flight termination from the ground could result in striking multiple persons on the ground causing injury or fatality. PE-3. Potential for lost link involving multiple UAS under common causal conditions or from design / validation inadequacy that affects multiple UAS and multi-UAS operations could cause multiple UAS to crash into a one or more buildings /obstacles resulting in widespread secondary injury from UAS debris and/or building damage.	Micro UAS (0 < W≤ 4.4 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Mini UAS (4.4 < W ≤ 20 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Small UAS (20 < W ≤ 55 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote

Preliminary Risk Assessment Summary – Aircraft Lost Communication / Control Link (continued)

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-3 Aircraft Lost Communication / Control Link Operating Environment: • Suburban / Urban / Congested Locations • Moderate-to-High-Density Operations • Single- or Multi-UAS Operations • Semi- or Fully-Autonomous Control • BVLOS	PE-1: Inability to control the aircraft from the ground and/or monitor aircraft position could potentially result in multiple collisions with other UAS or a manned aircraft operating in the area. PE-2: Inability to control the aircraft from the ground and/or monitor aircraft position involving multiple UAS could result in widespread injuries / fatalities to persons on the ground. PE-3. Potential for lost link involving many UAS, particularly from design / validation inadequacy that affects multiple UAS and multi-UAS operations could cause multiple UAS to crash into a one or more buildings /obstacles resulting in widespread secondary injury from UAS debris and/or building damage.	Micro UAS (0 < W≤ 4.4 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Mini UAS (4.4 < W ≤ 20 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Small UAS (20 < W ≤ 55 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote

Preliminary Risk Assessment Summary – Aircraft Loss of Navigation Capability

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-4 **Aircraft Loss of Navigation Capability** Operating Environment: • Remote/Rural Location • Low-Density Operations • Single UAS • Manual Control by Pilot • VLOS / BVLOS	PE-1: Inability to fly the desired trajectory causes the UAS to exit the assigned geo-fence and leads to a potential collision with another UAS or a manned aircraft operating in the area. PE-2: Inability to fly the desired trajectory causes the UAS to exit the assigned geo-fence and could result in striking a person on the ground causing injury or fatality. PE-3: Inability to fly the desired trajectory causes the UAS to exit the assigned geo-fence, and the aircraft crashes into a building/obstacle, resulting in secondary injury to person(s) on the ground from UAS debris or building damage.	Micro UAS (0 < W≤ 4.4 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
		Mini UAS (4.4 < W ≤ 20 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
		Small UAS (20 < W ≤ 55 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Extremely Remote

Preliminary Risk Assessment Summary – Aircraft Loss of Navigation Capability (continued)

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-4 **Aircraft Loss of Navigation Capability** Operating Environment: • Suburban / Urban Location • Moderate-to-High-Density Operations • Single- or Multi-UAS Operations • Semi-Autonomous Control • BVLOS	PE-1: Inability to fly the desired trajectory causes the UAS location to be inaccurate or undetermined, In moderate-to-high-density airspace, this could potentially result in multiple collisions with other UAS or a manned aircraft operating in the area. PE-2: Inability to fly the desired trajectory causes the UAS location to be inaccurate or undetermined and could result in striking multiple persons on the ground causing injury or fatality. PE-3. Potential for multiple UAS to exit the geo-fence and their locations to be inaccurate or undetermined could cause multiple UAS to crash into a one or more buildings /obstacles resulting in widespread secondary injury from UAS debris and/or building damage. .	Micro UAS (0 < W≤ 4.4 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Mini UAS (4.4 < W ≤ 20 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Small UAS (20 < W ≤ 55 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote

Preliminary Risk Assessment Summary – Aircraft Loss of Navigation Capability (continued)

<table>
<tr><th>Hazard Description</th><th>Possible Effects</th><th>Vehicle Weight Class</th><th>Vehicle Configuration</th><th>Severity</th><th>Safety Objective</th></tr>
<tr><td rowspan="9">VH-4
Aircraft Loss of Navigation Capability

Operating Environment:
• Suburban / Urban / Congested Locations
• Moderate-to-High-Density Operations
• Single- or Multi-UAS Operations
• Semi- or Fully-Autonomous Control
• BVLOS</td><td rowspan="9">PE-1: Inability to fly the desired trajectory causes the UAS location to be inaccurate or undetermined, which creates the possibility for widespread collisions under common causal conditions (e.g., lost GPS signal or network loss) with other UAS or a manned aircraft.

PE-2: Inability to fly the desired trajectory causes the UAS location to be inaccurate or undetermined and could result in striking multiple persons on the ground causing numerous injuries or fatalities.

PE-3. Potential for navigation failures involving many UAS from error propagation associated with multi-UAS operations could cause multiple UAS to crash into a one or more buildings /obstacles resulting in widespread secondary injury from UAS debris, building damage, and/or post-impact fire.</td><td rowspan="3">Micro UAS
(0 < W≤ 4.4 lbs)</td><td>Fixed Wing</td><td>PE-1: Catastrophic
PE-2: Catastrophic
PE-3: Major</td><td>PE-1: Extremely Improbable
PE-2: Extremely Improbable
PE-3: Remote</td></tr>
<tr><td>Multirotor</td><td>PE-1: Catastrophic
PE-2: Catastrophic
PE-3: Major</td><td>PE-1: Extremely Improbable
PE-2: Extremely Improbable
PE-3: Remote</td></tr>
<tr><td>Helicopter</td><td>PE-1: Catastrophic
PE-2: Catastrophic
PE-3: Major</td><td>PE-1: Extremely Improbable
PE-2: Extremely Improbable
PE-3: Remote</td></tr>
<tr><td rowspan="3">Mini UAS
(4.4 < W ≤ 20 lbs)</td><td>Fixed Wing</td><td>PE-1: Catastrophic
PE-2: Catastrophic
PE-3: Major</td><td>PE-1: Extremely Improbable
PE-2: Extremely Improbable
PE-3: Remote</td></tr>
<tr><td>Multirotor</td><td>PE-1: Catastrophic
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PE-2: Extremely Improbable
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PE-3: Major</td><td>PE-1: Extremely Improbable
PE-2: Extremely Improbable
PE-3: Remote</td></tr>
<tr><td rowspan="3">Small UAS
(20 < W ≤ 55 lbs)</td><td>Fixed Wing</td><td>PE-1: Catastrophic
PE-2: Catastrophic
PE-3: Hazardous</td><td>PE-1: Extremely Improbable
PE-2: Extremely Improbable
PE-3: Extremely Remote</td></tr>
<tr><td>Multirotor</td><td>PE-1: Catastrophic
PE-2: Catastrophic
PE-3: Major</td><td>PE-1: Extremely Improbable
PE-2: Extremely Improbable
PE-3: Remote</td></tr>
<tr><td>Helicopter</td><td>PE-1: Catastrophic
PE-2: Catastrophic
PE-3: Hazardous</td><td>PE-1: Extremely Improbable
PE-2: Extremely Improbable
PE-3: Extremely Remote</td></tr>
</table>

Preliminary Risk Assessment Summary – Unsuccessful Landing

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-5 Unsuccessful Landing Operating Environment: • Remote/Rural Location • Low-Density Operations • Single UAS • Manual Control by Pilot • VLOS / BVLOS	PE-1: Abnormal runway contact or crash on landing causes vehicle break-up, resulting in crash debris and/or post-impact fire injuring ground crew.	Micro UAS ($0 < W \leq 4.4$ lbs)	Fixed Wing	PE-1: Minor	PE-1: Probable
			Multirotor	PE-1: Minor	PE-1: Probable
			Helicopter	PE-1: Minor	PE-1: Probable
		Mini UAS ($4.4 < W \leq 20$ lbs)	Fixed Wing	PE-1: Minor	PE-1: Probable
			Multirotor	PE-1: Minor	PE-1: Probable
			Helicopter	PE-1: Minor	PE-1: Probable
		Small UAS ($20 < W \leq 55$ lbs)	Fixed Wing	PE-1: Major	PE-1: Remote
			Multirotor	PE-1: Major	PE-1: Remote
			Helicopter	PE-1: Major	PE-1: Remote

Preliminary Risk Assessment Summary – Unsuccessful Landing (continued)

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-5 Unsuccessful Landing Operating Environment: • Suburban / Urban Location • Moderate-to-High-Density Operations • Single- or Multi-UAS Operations • Semi-Autonomous Control • BVLOS	PE-1: Abnormal runway contact or crash on landing causes vehicle break-up, resulting in crash debris and/or post-impact fire injuring people on the ground other than UAS crew.	Micro UAS (0 < W≤ 4.4 lbs)	Fixed Wing	PE-1: Minor	PE-1: Probable
			Multirotor	PE-1: Minor	PE-1: Probable
			Helicopter	PE-1: Minor	PE-1: Probable
		Mini UAS (4.4 < W ≤ 20 lbs)	Fixed Wing	PE-1: Major	PE-1: Remote
			Multirotor	PE-1: Major	PE-1: Remote
			Helicopter	PE-1: Major	PE-1: Remote
		Small UAS (20 < W ≤ 55 lbs)	Fixed Wing	PE-1: Hazardous	PE-1: Extremely Remote
			Multirotor	PE-1: Hazardous	PE-1: Extremely Remote
			Helicopter	PE-1: Hazardous	PE-1: Extremely Remote

Preliminary Risk Assessment Summary – Unsuccessful Landing (continued)

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-5 Unsuccessful Landing Operating Environment: • Suburban / Urban / Congested Locations • Moderate-to-High-Density Operations • Single- or Multi-UAS Operations • Semi- or Fully-Autonomous Control • BVLOS	PE-1: Abnormal runway contact or crash on landing causes vehicle break-up, resulting in potentially serious injuries to multiple people on the ground from crash debris and/or post-impact fire in a congested area.	Micro UAS ($0 < W \leq 4.4$ lbs)	Fixed Wing	PE-1: Major	PE-1: Remote
			Multirotor	PE-1: Major	PE-1: Remote
			Helicopter	PE-1: Major	PE-1: Remote
		Mini UAS ($4.4 < W \leq 20$ lbs)	Fixed Wing	PE-1: Hazardous	PE-1: Extremely Remote
			Multirotor	PE-1: Hazardous	PE-1: Extremely Remote
			Helicopter	PE-1: Hazardous	PE-1: Extremely Remote
		Small UAS ($20 < W \leq 55$ lbs)	Fixed Wing	PE-1: Hazardous	PE-1: Extremely Remote
			Multirotor	PE-1: Hazardous	PE-1: Extremely Remote
			Helicopter	PE-1: Hazardous	PE-1: Extremely Remote

Preliminary Risk Assessment Summary – Unintentional / Unsuccessful Flight Termination

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-6 Unintentional / Unsuccessful Flight Termination Operating Environment: • Remote/Rural Location • Low-Density Operations • Single UAS • Manual Control by Pilot • VLOS / BVLOS	PE-1: Vehicle debris from UAS forced crash landing in an unsafe location injures UAS ground crew. PE-2: Post-crash fire from UAS forced crash landing in an unsafe location threatens wildlife and the environment.	Micro UAS (0 < W≤ 4.4 lbs)	Fixed Wing	PE-1: Minor PE-2: Minor	PE-1: Probable PE-2: Probable
			Multirotor	PE-1: Minor PE-2: Minor	PE-1: Probable PE-2: Probable
			Helicopter	PE-1: Minor PE-2: Minor	PE-1: Probable PE-2: Probable
		Mini UAS (4.4 < W ≤ 20 lbs)	Fixed Wing	PE-1: Minor PE-2: Minor	PE-1: Probable PE-2: Probable
			Multirotor	PE-1: Minor PE-2: Minor	PE-1: Probable PE-2: Probable
			Helicopter	PE-1: Minor PE-2: Minor	PE-1: Probable PE-2: Probable
		Small UAS (20 < W ≤ 55 lbs)	Fixed Wing	PE-1: Minor PE-2: Major	PE-1: Probable PE-2: Remote
			Multirotor	PE-1: Minor PE-2: Major	PE-1: Probable PE-2: Remote
			Helicopter	PE-1: Minor PE-2: Major	PE-1: Probable PE-2: Remote

Preliminary Risk Assessment Summary – Unintentional / Unsuccessful Flight Termination (continued)

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-6 Unintentional / Unsuccessful Flight Termination Operating Environment: • Suburban / Urban Location • Moderate-to-High-Density Operations • Single- or Multi-UAS Operations • Semi-Autonomous Control • BVLOS	PE-1: Forced crash landing of one or more UAS collides with a ground vehicle or causes an accident involving a ground vehicle resulting in multiple injuries or fatalities. PE-2: Vehicle debris and/or post-impact fire from one or more UAS forced crash landings in an unsafe location injures people on the ground.	Micro UAS (0 < W≤ 4.4 lbs)	Fixed Wing	PE-1: Hazardous PE-2: Major	PE-1: Extremely Remote PE-2: Remote
			Multirotor	PE-1: Hazardous PE-2: Major	PE-1: Extremely Remote PE-2: Remote
			Helicopter	PE-1: Hazardous PE-2: Major	PE-1: Extremely Remote PE-2: Remote
		Mini UAS (4.4 < W ≤ 20 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote
			Helicopter	PE-1: Catastrophic PE-2: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote
		Small UAS (20 < W ≤ 55 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote
			Helicopter	PE-1: Catastrophic PE-2: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote

Preliminary Risk Assessment Summary – Unintentional / Unsuccessful Flight Termination (continued)

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-6 Unintentional / Unsuccessful Flight Termination Operating Environment: • Suburban / Urban / Congested Locations • Moderate-to-High-Density Operations • Single- or Multi-UAS Operations • Semi- or Fully-Autonomous Control • BVLOS	PE-1: Forced crash landings of potentially many UAS collide with a ground vehicle or causes an accident involving a ground vehicle resulting in multiple injuries or fatalities. PE-2: Vehicle debris and/or post-impact fire from potentially many UAS forced crash landings in an unsafe location in a congested area results in multiple injuries or possible fatalities to people on the ground.	Micro UAS ($0 < W \leq 4.4$ lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic	PE-1: Extremely Improbable PE-2: Extremely Improbable
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic	PE-1: Extremely Improbable PE-2: Extremely Improbable
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic	PE-1: Extremely Improbable PE-2: Extremely Improbable
		Mini UAS ($4.4 < W \leq 20$ lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic	PE-1: Extremely Improbable PE-2: Extremely Improbable
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic	PE-1: Extremely Improbable PE-2: Extremely Improbable
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic	PE-1: Extremely Improbable PE-2: Extremely Improbable
		Small UAS ($20 < W \leq 55$ lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic	PE-1: Extremely Improbable PE-2: Extremely Improbable
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic	PE-1: Extremely Improbable PE-2: Extremely Improbable
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic	PE-1: Extremely Improbable PE-2: Extremely Improbable

Preliminary Risk Assessment Summary – Failure/Inability to Avoid Collision with Terrain and/or Fixed or Moving Obstacle

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-7 Failure/Inability to Avoid Collision with Terrain and/or Fixed or Moving Obstacle Operating Environment: • Remote/Rural Location • Low-Density Operations • Single UAS • Manual Control by Pilot • VLOS / BVLOS	PE-1: Collision with another UAS or a manned aircraft operating in the area or with a vehicle on the ground. PE-2: Uncontrolled descent toward terrain could result in striking a person on the ground or in a ground vehicle causing injury or fatality. PE-3: Collision with infrastructure (building, bridge, power lines, sub-station, etc.) or other obstacle results in secondary injury to people on the ground from UAS debris, building damage, or fire from downed high-voltage power lines.	Micro UAS (0 < W≤ 4.4 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Minor	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Probable
		Mini UAS (4.4 < W ≤ 20 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
		Small UAS (20 < W ≤ 55 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Hazardous PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Hazardous PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Hazardous PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Remote PE-3: Extremely Remote

Preliminary Risk Assessment Summary – Failure/Inability to Avoid Collision with Terrain and/or Fixed or Moving Obstacle (continued)

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-7 Failure/Inability to Avoid Collision with Terrain and/or Fixed or Moving Obstacle Operating Environment: • Suburban / Urban Location • Moderate-to-High-Density Operations • Single- or Multi-UAS Operations • Semi-Autonomous Control • BVLOS	PE-1: Collision with another UAS or a manned aircraft operating in the area or with a vehicle on the ground. PE-2: Uncontrolled descent toward terrain could result in striking persons on the ground or in a ground vehicle, potentially causing multiple injuries or fatalities. PE-3: Collision with infrastructure (building, bridge, power lines, sub-station, etc.) or other obstacle results in secondary injury to people on the ground from UAS debris, building damage, or fire from downed high-voltage power lines.	Micro UAS (0 < W≤ 4.4 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Mini UAS (4.4 < W ≤ 20 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Small UAS (20 < W ≤ 55 lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote

Preliminary Risk Assessment Summary – Failure/Inability to Avoid Collision with Terrain and/or Fixed or Moving Obstacle (continued)

Hazard Description	Possible Effects	Vehicle Weight Class	Vehicle Configuration	Severity	Safety Objective
VH-7 Failure/Inability to Avoid Collision with Terrain and/or Fixed or Moving Obstacle Operating Environment: • Suburban / Urban / Congested Locations • Moderate-to-High-Density Operations • Single- or Multi-UAS Operations • Semi- or Fully-Autonomous Control • BVLOS	PE-1. Collision with another UAS or a manned aircraft operating in the area or with a vehicle on the ground. There is a potential for widespread collisions involving multiple UAS PE-2: Uncontrolled descent toward terrain could result in widespread injuries / fatalities to persons on the ground. PE-3. Potential for widespread collisions with infrastructure (building, bridge, power lines, sub-station, etc.) or other obstacle results in secondary injury to people on the ground from UAS debris, building damage, or fire from downed high-voltage power lines.	Micro UAS ($0 < W \leq 4.4$ lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Mini UAS ($4.4 < W \leq 20$ lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
		Small UAS ($20 < W \leq 55$ lbs)	Fixed Wing	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote
			Multirotor	PE-1: Catastrophic PE-2: Catastrophic PE-3: Major	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Remote
			Helicopter	PE-1: Catastrophic PE-2: Catastrophic PE-3: Hazardous	PE-1: Extremely Improbable PE-2: Extremely Improbable PE-3: Extremely Remote

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