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Unmanned Aerial System Integration into the National Airspace System and Airports: Risk Mitigation using Content Analysis Methodology

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Unmanned Aerial System Integration into the National Airspace System and Airports: Risk Mitigation using Content Analysis Methodology

by

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The undersigned committee, having examined the attached thesis "Unmanned Aerial System Integration into the National Airspace System and Airports: Risk Mitigation Using Content Analysis Methodology," by Bhoomin Bhupendrabhai Chauhan hereby indicate its unanimous approval.

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Abstract

Title: Unmanned Aerial System Integration into the National Airspace System and Airports: Risk Mitigation Using Content Analysis Methodology

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Over the last few years, the use of unmanned aerial systems (UAS) has significantly increased. With an increase in the use of UASs, the number of UAS sightings near manned aircraft and airports have also increased, as shown by the Federal Aviation Administration (FAA)(FAA, 2019a). Although not every near sighting had a severe consequence associated with it, the risks were still present. As UASs are becoming more readily available to the general public, the risks present due to UASs flying in the National Airspace System (NAS) and near airports is also increasing. For the study, incident and accident reports were obtained from the National Transportation Safety Board (NTSB) and the Aviation Safety Report System (ASRS) databases. After the reports were downloaded, reports that did not have information regarding UASs were discarded. Two instrument forms were developed, one for NTSB reports and one for ASRS reports. Next, qualitative content analysis was used to identify the most frequently occurring Human Factors Analysis and Classification System (HFACS) of the contributing factors and probable cause(s) of the reported incident or accident. After the HFACS categories were identified for the NTSB and ASRS reports, all the incidents that had a similar chain of events were grouped for representation in the Bow-tieXP software. After the analysis,

a total of seven bow-tie diagrams were created with each representing the identified event identified from the content analysis. The bow-tie diagrams helped identify the threats that could lead to the occurrence of the top event. If the top event occurred, the consequences arising from them were documented. The bow-tie diagram also helped identify barriers that could be used so that the risks associated with each threat and consequence were mitigated. After the bow-tie diagrams were completed, recommendations were made for safe operations of UASs in the NAS and airports.

Table of Content

List of Figures

List of Tables

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Next, I would like to thank Dr. Stephen Cusick for his support during the early phases of my thesis, particularly, on how I should approach the research question and what I need to look for in my data. Dr. Cusick provided valuable input during the thesis proposal and the thesis writing, mainly, regarding aviation safety and how it can be implemented for UAS operations. Dr. Cusick was available to help me whenever I had any questions regarding aviation, and his help has helped shaped this thesis the way it was intended.

Next, I would like to thank Dr. Heidi Hatfield Edwards. Dr. Edwards' suggestion helped me format and write my thesis in such a manner that it would be easily read by a person outside of aviation. She also provided vital recommendations regarding the content of my thesis and how it should be written. Her suggestions have helped me to understand better how to write a research paper.

Lastly, I would like to thank Dr. Brooke Wheeler, College of Aeronautics faculty and Writer's Den volunteer, for her patience and help in making this thesis written in accordance with APA format.

Dedication

I want to dedicate my thesis to my family who has always been there for me, have always supported me, and have stood by my side during both good and bad times. My father, Dr. Bhupendrabhai M Chauahn, and mother, Dr. Minaxi B Chauhan, have always been a source of constant support and motivation since I came to the United States to pursue my graduate degree. I owe everything to them. It is because of them that I am here today and able to accomplish everything I have accomplished. Nothing would have been possible without both of your love and affection. I would also like to thank my grandmother whose love and prayers have always kept me in good health and to stay positive throughout my endeavors.

I would also like to dedicate my thesis to my sister, Preet. Thank you for listening to me and talking to me whenever I struggled or did not feel motivated enough to pursue my work. Thank you for always being there for me when I needed you. Your presence continues to always bring a smile to my face and gives me the ray of light that I need to push forward even beyond my capabilities.

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Chapter 1

Introduction

Problem Statement

The purpose of this study is to determine the risks associated with integrating UAS in the NAS and airports. The current study examines incident and accident reports through content analysis. The goal of the study was to identify safety recommendations for UAS operators in the NAS or near airports to mitigate or minimize risks.

Operational Definitions

The operational definitions have been established for the study and are discussed in this section. UAS is commonly also referred to as an unmanned aerial vehicle (UAV) or a drone. It is an aircraft model which can operate without a pilot onboard. It can operate with the help of a communication link that is established between the pilot and the UAS.

NTSB reports, in the context of the current study, are defined as UAS incident and accident reports obtained from the NTSB Aviation Accident & Synopses database. The date range of the reports used in the study is January 2008 through January 2018. Reports were identified through searching on keyword strings consisting of UAV, UAS, drone for specific aircraft make and model.

ASRS reports, in the context of the current study, are defined as UAS incident and accident reports obtained from the ASRS website. The date range of the reports used in the study is January 2008 through January 2018. The reports were identified through entering the term UAV as the aircraft make and model.

The NAS, in general terms, is defined as different classes or layers of separation for the aircraft to fly. These classes are determined by the volume of traffic that passes through them. The different classes come with their own set of regulations and operational limitations for the aircraft (including the UAS) flying through them.

Airports are defined as a facility, area of land, or area of water, which has been designated for use for landing, or take-off of aircraft (FAA, 2016b). This also includes the area that is used for airport facilities, operations, and buildings.

Contributing factor, in the context of the current study, is defined as one of the primary causes or factors that lead to UAS incidents or accidents.

Bow-tie diagram, in the context of the current study, is defined as a visual tool that provides an overview of multiple, plausible scenarios and displays the type of barriers that can be placed to control the threats that may arise for a given scenario (CGE Risk Management Solutions, n.d.).

Barriers, for the current study, are defined using two terms: control barrier and recovery barrier (CGE Academy, n.d.). Control barriers are defined as a barrier that will prevent a threat from occurring, but if the threat still presents itself, it will reduce the impact so that the top event does not occur. Recovery barrier is defined as a barrier that is placed to make sure that if the top event is reached, the scenario does not escalate into a severe consequence. The recovery barrier can also act as a way to mitigate the risk.

UAS incidents are defined as an event that occurs when an operating UAS suffers from a sudden malfunction. This includes but is not limited to mechanical failure, resulting in the loss of control of the UAS. It also includes the remotely located pilot losing situational awareness of the UAS that he or she is operating resulting in either a loss of communication link or near collision with an object, or terrain in the path of the UAS.

UAS accidents are defined as a UAS involved in a severe crash that may or may not be dangerous depending upon the consequence of the crash.

Risk, in the context of the current study, is defined as the chance or the probability that a person on the ground or passengers in manned aircraft will be affected or harmed because of the hazard of operating a UAS. These losses are not limited to humans because risks can also apply to the loss or damage of an aircraft component, damage to property, failure of equipment, and adverse effect on the surrounding environment.

Background

Recently, UAS popularity has increased. It is no longer limited to military use as the popularity of UAS use is also increasing among civilian or recreational use such as for film making, merchandise delivery, aerial photography, etc. (Cho, Cho, & Jeon, 2016). UAS accidents are increasingly causing damage to humans and property. The rise in the number of accidents has brought to light the concern for safety and security of operating a UAS. Cho et al. states that “Over the same number of flight hours, accidents caused by drones amount to 50 times the number of general flight accidents, and accidents caused by users’ mistakes while controlling the drone make up 32% of all relevant accidents” (p. 345).

With advancements in technology and the increased use of UAS for military operations, the operational capabilities have been proven for potential civil and commercial UAS use (Weibel, 2005). With the potential of UAS for civil and commercial use, there is a demand for more federal regulations to help guide safe operations for UAS. The lack of adequate federal regulations has proven to be an obstacle for safe UAS operations.

With the fast development of miniaturization and low-cost manufacturing of simple consumer electronics, UASs or drones are readily available to the general population through online vendors and electronics supermarkets (La Cour-Harbo, 2017). With easy availability, there is an increase in civil UAS use. When a UAS is operated in the NAS or near airports, it can pose an imminent threat to aircraft that are flying in the NAS, and to equipment or ground personnel at the airport. Military or government UAS use does not pose a significant threat when compared to civilian use as the majority of the UAS used for military missions are flown under strict regulations, but that does not mean that military operated UAS are entirely safe. Equipment failure, loss of communication link, or loss of situational awareness pose a threat. The pilots may not be aware of the airspace or regulatory limitations of operating a UAS in that particular area. During such use, if the UAS is operated near an airport, it may come in the approach path of an arriving aircraft posing a severe threat of mid-air collision. Similarly, if the UAS is operated above the designated altitude, it may result in a similar severe consequence.

Over the last few years, as displayed in Figure 1, the number of reported UAS sightings has steadily increased, and there have been instances where the presence of UASs near an aircraft or a helicopter has encountered a poor outcome. For example, on September 21, 2017, a United States (U.S.) Black Hawk helicopter was involved in a collision with an unmanned aircraft while it was performing a routine low-altitude flight in Staten Island, New York (Wallace, Haritos, & Robbins, 2018). Even though the helicopter made it back safely, due to the collision, the rotor blades of the helicopter were severely damaged.

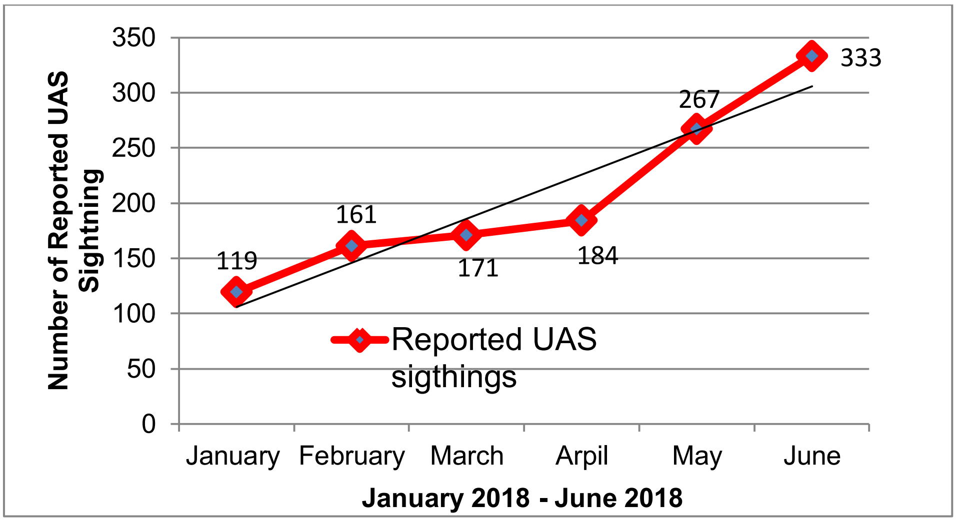

Figure 1: Increase in UAS Sightings (FAA, 2019a)

Similarly, in 2014, The New York City Police Department alleged that one of their helicopters was struck twice by a UAS at 2,000 feet. Even in this case, the helicopter made it back safely (Wallace et al., 2018). Such incidents were not limited to the U.S. in 2017; a Canadian SkyJet King Air-100 Turboprop was also struck by a UAS while on approach to its destination.

With a projected increase in the number of UAS use, the number of sightings will also be on the rise. Depending upon the nature of the violation of these sightings, the number of incidents and accidents may also increase. It is essential that necessary steps are taken to ensure that any risk that is associated with the operation of UAS is mitigated and brought to an acceptable level.

Research Questions

The research questions answered through conducting this study are listed below:

RQ1: What are the risks associated with integrating UAS into the NAS and airports?

RQ2: What are recommendations to mitigate or reduce the risks of UAS operation into the NAS and airports?

Significance of Study

As previously stated, there is an increase in the use of UAS and related incidents and accidents. UAS use is projected to continue to increase. It is crucial for UAS operators to understand the associated risks when flying UASs into the NAS and near airports. While military use is carried out under strict regulation and supervision, an anomaly can happen and result in serious consequences. Civilian use may be carried out with or without concern for rules that regulate its use, and for a myriad of reasons that can result in a UAS incident and accident. This study, as discussed in the methodology chapter, will develop themes from the reports identified through content analysis. Content analysis, as a methodology, can be used to analyze documents as it allows the researcher to understand the collected data and develop a systematic description of a phenomenon (Elo & Kyngäsh, 2008). Content analysis will point out the most frequently occurring contributing factors and probable cause(s) that have led to UAS incidents and accidents. The contributing factors and probable cause(s) will then be visually represented in a bow-tie diagram to identify the risks associated with each contributing factor. Also, the bow-tie diagram will assist through displaying the barriers that can be implemented resulting in mitigated or reduced risks. The bow-tie diagram in acting as a visual representation will display what needs to be done regarding which barriers need to be implemented so that the risk level is brought to an acceptable level.

The process of integrating threats arising from the contributing factors and probable cause(s) identified through the content analysis and displayed through a bow-tie diagram will provide a UAS risk assessment. This will then result in recommendations to mitigate or reduce risks by recommending barriers.

Generalizability

Generalizability of a study indicates the extent to which the study can be generalized over a population. The results of this study will focus on the reports that were used as part of the data collection procedure. This study will account for both military and civilian use in terms of integrating UASs into the NAS and near airports.

The methodology chapter will discuss the data analysis for each NTSB and ASRS report to identify contributing factors and probable cause(s). After thoroughly analyzing the reports, the most frequently occurring contributing factors and probable cause(s) will be noted. The reports obtained have information regarding UAS incidents and accidents for both military and civilian use. Therefore, the barriers identified for each risk associated with the most frequently occurring contributing factor can be generalizable for different types of UAS use. This is due to the contributing factors and probable cause(s) identified as the most common causes of UAS incidents and accidents. Therefore, the identified barriers can act as recommendations on what needs to be implemented to provide adequate measures and to ensure safe integration all type of UAS.

Limitations

Limitations of this study can be listed as factors that limit the scope and reach of the study.

The first limitation of the study is that the reports that were analyzed have been collected from the ASRS website and the NTSB website. However, the reports that are submitted to the ASRS database are generally submitted voluntarily making it difficult to predict the accuracy of the data available.

A second limitation is that it also needs to be noted that not all UAS sightings or incidents and accidents are reported on the ASRS database, which will ultimately result in not all contributing factors and probable cause(s) being identified.

A third and similar limitation will also arise when using the NTSB accident database. UAS accident reports generated from the NTSB database is comprised of Part 121 and Part 135 reports. The FAA authorizes air carriers to operate scheduled air service under Federal Aviation Regulation (FAR) 121 certificate (FAA, 2018c). Air carriers that are generally allowed to operate under Part 121 include U.S. based large airlines, regional airlines, and all-cargo airlines. Air carriers that are authorized to operate under Part 135 vary from small single-engine aircraft operators to large operators that often provide a network to move passengers and cargo for Part 121 carriers (FAA, 2018d). The reports will need to be carefully analyzed to make sure that Part 121 and Part 135 reports are not included with UAS incidents and accident reports.

A fourth limitation of the study is that the data available for use constitute a small number of the actual UAS incidents and accidents. This does not include UAS sightings such as a UAS sighted above designated operational altitude or observed UASs operating near an active runway or an airport. UAS sighting, if not dangerous at this point, can prove to be fatal if corrective measures are not taken. Because there is no way of knowing the actual number of UAS incidents and accidents, there is a lack of available data for a comprehensive risk assessment of UAS integration into the NAS and airports.

Delimitations

Delimitations for a study are the methods used to ensure study boundaries are maintained for the scope of the study.

The first delimitation employed is that the reports downloaded from the NTSB website were thoroughly studied to ensure that reports without information regarding UAS incidents were discarded. Therefore, adequate consistency was maintained in terms of information available from each ASRS and NTSB report.

The second delimitation employed was the development of themes for contributing factors and probable cause(s) that were extracted from the reports. These themes acted as a summary of the contributing factors and probable cause(s) found in the reports. Using a different bow-tie diagram for each contributing factor and probable cause would result in repetition of the barriers resulting in the same contributing factors and probable cause(s) being displayed in multiple bow-tie diagrams and would increase the complexity of interpreting the task of risk assessment for each contributing factor and probable cause. To ensure that this does not happen from among themes identified in the content analysis, recurring contributing factors and probable cause(s) were sorted and incorporated into bow-tie diagrams. This made it easier to identify recommendations that should be implemented from the identified barriers affiliated from the contributing factor and probable cause.

Chapter 2

Literature Review

National Airspace System

The NAS, in general, can be defined as different categories or demarcation for all aircraft to fly over the U.S. airspace (U.S. Department of Transportation, 2017). The Federal Aviation Act of 1958 established the FAA, which is responsible for the control of the navigational airspace over the U.S. After its creation, the FAA created the NAS to establish a safe and efficient airspace environment for civil, commercial, and military aviation operations. The NAS has two categories of airspace/airspace areas, namely Regulatory Airspace and Non-regulatory Airspace.

The regulatory airspace consists of category A, B, C, D, and E airspace areas, restricted and prohibited area while non-regulatory airspace consists of military operation areas, warning areas, alert areas, and controlled firing areas (U.S. Department of Transportation, 2017). In these two categories, the airspace is further categorized, according to the U.S. Department of Transportation, "these two categories are divided into four types. These types are Controlled, Uncontrolled, Special use, and Other Airspace" (p. 3-1-1).

These different categories of airspace, as shown in Figure 2, are devised depending upon the complexity or density of aircraft movements, the nature of operations conducted with the airspace, the level of safety required, and national and public interests (U.S. Department of Transportation, 2017).

Controlled airspace is more of a generic term used to identify the different classes of airspace, mainly Class A, Class B, Class C, Class D, and Class E airspace. Controlled airspace is the defined dimensions within which air traffic controller (ATC) service is provided to the Instrument Flight Rules (IFR) flights, and Visual Flight Rules (VFR) flights according to the airspace classification.

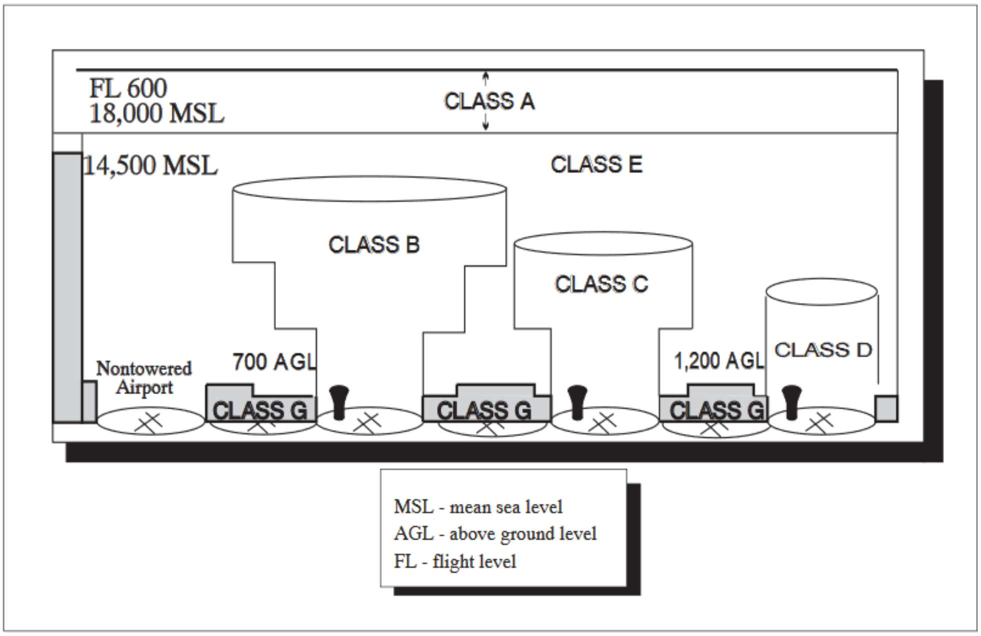

Figure 2: Different Airspace Classes With Their Respective Upper Limits (U.S. Department of Transportation, 2017, p. 3-2-1)

Class A Airspace. "Class A airspace is generally that airspace that is from 18,000 mean sea level (MSL) up to and including flight level (FL) 600. Class A airspace also includes the airspace overlying the waters within 12 nautical miles (NM) off the coast of 48 contiguous states and Alaska" (U.S. Department of Transportation, 2017, p. 3-2-2). Class A also includes any designated international airspace that is beyond 12 NM off the coast of 48 contiguous states and Alaska and is within areas of domestic radio navigational signal or is within ATC radar coverage.

Class B Airspace.“Class B airspace is generally that airspace from the surface to 10,000 MSL surrounding the nation’s busiest airport in terms of IFR operations or passenger enplanements” (U.S. Department of Transportation, 2017, p. 3-2-2). The configuration of each Class B airspace area is individually customized and consists of a surface area and more than two layers that are designed to contain all the published instrument procedures once an aircraft enters the designated airspace. An ATC clearance is mandatory for all aircraft to operate in an area and the cleared aircraft receive separation services within the airspace.

Class C Airspace. "Class C airspace starts from the surface to 4,000 MSL surrounding those airports that have an operational control tower, have radar approach control as well as have a certain number of IFR operations and passenger enplanements" (U.S. Department of Transportation, 2017. p. 3-2-4). Class C airspace is also customized for each airport. The airspace usually consists of 5 NM radius core surface area that goes up to 4,000 feet above the airport elevation and a 10 NM radius shelf area that is no lower than 1,200 feet to 4,000 feet above the airport elevation.

Class D Airspace. "Class D airspace extends upward from the surface to 2,500 feet above the airport elevation (charted in MSL) surrounding those airports that have an operational control tower" (U.S. Department of Transportation, 2017, p. 3-2-8). The configuration of each Class D airspace like

Class A, B, and C are individually tailored, and whenever instrument procedures are published, the airspace will generally be designed to contain the procedures. Any class D surface may be designated as full-time (24-hour operations) or part-time operation.

Class E Airspace. Class E airspace is controlled airspace that is designated to serve a variety of terminal or en route purposes. In class E airspace, pilot certification and specific equipment are not required with an exception for any operation at a designated lower altitude.

U.S. Department of Transportation (2017) defines Class E as follows:

> Class E airspace extends upwards from 14,500 feet MSL to, but not including 18,000 feet MSL overlying 48 contiguous states including Alaska, District of Columbia, the waters within 12 NM from the coast of the 48 contiguous states and Alaska. Class E airspace excludes the Alaska Peninsula west of longitude 160° 00'00''W, airspace below 1,500 MSL above the surface of the earth unless specifically designed lower (p. 3-2-9).

Class G Airspace. Class G airspace or uncontrolled airspace is that portion of the airspace that is not designated as Class A, Class B, Class C, Class D, or Class E airspace (U.S. Department of Transportation, 2017).

Special Use Airspace. Particular use airspace consists of that airspace where any activities must be confined because of the nature of their operations or because of limitations imposed upon the aircraft operations that are not involved in any of those activities (U.S. Department of Transportation, 2017).

Except for controlled firing areas (CFAs), all Special Use Airspace areas are depicted on the aeronautical charts.

Prohibited and restricted areas are regulatory special use airspace established in 14 CFR part 73 through the rule-making process. According to the U.S. Department of Transportation (2017), "Warning areas, military operations, alert areas, and controlled firing fall under non-regulatory special use airspace. Special use airspace except for CFAs are charted on IFR or visual charts and include the hours of operations, altitudes, and the controlling agency" (p. 3-4-1).

Other Airspace Area. Another type of airspace area, particularly, in terms of airport advisory and information services can be broken down into two types:

1) Local Airport Advisory (LAA)
2) Remote Airport Information Service

LAA is available only in Alaska and is operated within 10 statute miles of an airport where a control tower is not operating but where a flight service stations (FSS) is located at an airport (U.S. Department of Transportation, 2017). At such locations near an airport, the FSS provides overall local airport advisory services to all departing and arriving flights.

Other special airspace areas include military training routes, Temporary Flight Restrictions, parachute jump aircraft operations, published VFR routes, Terminal Radar Service Area, and Weather Reconnaissance Area.

Airport Classification

The National Plan of Integrated Airport Systems (NPIAS) is a federal document that comprises all data related to the airports.

According to the U.S. Department of Transportation (2016):

> In the NPIAS, there are 3,340 airports. This number includes the 3,332 existing airports and eight proposed airports that are planned to open within five periods covered by the NPIAS (2017-2021) report. Public entities own Ninety-eight percent of the airports that are included in the NPIAS, and only 77 are privately owned (p. 3).

According to the U.S. Department of Transportation (2016), there are two main categories of airports: Primary and non-primary. Primary airports are any airports that are public airports receiving a scheduled air carrier service with more than 10,000 or more enplaned passengers per year. Primary airports are further categorized into four types consisting of large, medium, small and non-hub. Figure 3 shows the total number of airport present in each category.

Non-primary, on the other hand, are airports that are generally used by general aviation (GA) aircraft. According to the U.S. Department of Transportation (2016), “Non-primary commercial service airports, i.e., any airports receiving scheduled passenger service between 2,500 and 9,999 enplaned passenger per year, GA airports, and reliever airports fall under a non-primary airport category" (p. 3). In total, there are 2,950 airports. Non-primary airports are further categorized into national, regional, local, basic, and unclassified.

Primary Airports. There are a total of 382 primary airports in the U.S (U.S. Department of Transportation, 2016). These airports fall into four categories defined in statute as large, medium, small, and non-hub airports.

U.S. Department of Transportation (2016) state that “Large hubs are airports that each account for one percent or more of the total U.S. passenger enplanements” (p. 5). Some of the passengers using large hubs as their origin may fly from the local community while other passengers may be on connecting flights. Large hub airports tend to have commercial airlines and freight operations with minimal GA operations.

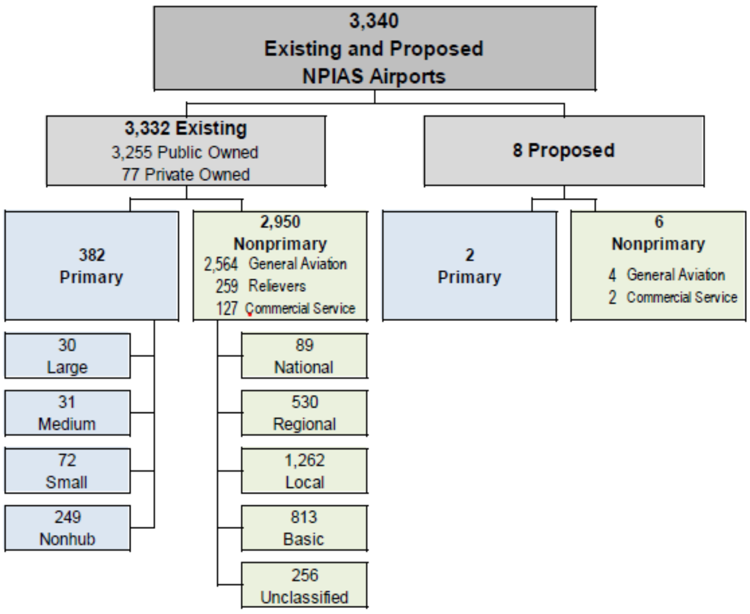

Figure 3: NPIAS Airports By Category, Total Number, And Use (U.S. Department of Transportation, 2016, p. 3)

U.S. Department of Transportation (2016) defines medium hubs as airports in the U.S. that account for between 0.25 percent and one percent of the total U.S. passenger enplanements. Large hubs and medium hubs can sufficiently handle air carrier operations, but medium hubs also handle substantial GA operations.

U.S. Department of Transportation (2016) defines "small hub airports as airports that have enplanement of .05 percent to 0.25 percent of total U.S. passenger enplanements" (p. 5). Currently, 72 small hub airports together account for almost nine percent of total enplanements.

U.S. Department of Transportation (2016) state that "Non-hub primary airports have an enplanement that is less than 0.05 percent of all commercial passenger enplanement but has more than 10,000 annual enplanements" (p. 6). At present, 249 non-hub primary airports together account for almost four percent of all enplanements. These airports are generally used for GA activity with an average of 95-based aircraft.

Non-Primary Airports. According to the U.S. Department of Transportation (2016), Non-primary airports are generally used for GA operations, which include 127 nonprimary commercial service, 259 relievers, and 2,564 GA airports (p. 6). Non-primary airports are further categorized depending upon their number and type of based aircraft, volume, and type of flights.

Non-Primary airports are further grouped into five categories. These categories are national, regional, local, basic, and unclassified. National airports are located in the metropolitan area of a city and are easily accessible to nearby business centers such as corporate headquarters, offices, and companies. They support flying throughout the nation and the world. These airports provide excellent alternatives for busy primary airports. Primary airports are any airports that are public airports receiving a scheduled air carrier service with more than 10,000 or more enplaned passengers per year. The FAA has designated 65 of these airports as relievers for primary airports (U.S. Department of Transportation, 2016). National airports have a high activity of jets and multiengine propeller aircraft.

Regional airports, such as national airports, are also located near metropolitan areas and serve a large population and communities (U.S. Department of Transportation, 2016). These airports primarily support the regional economy, community, and business and have long-distance flights. Regional airports have a high level of activity from jets and multiengine propeller aircraft.

Local airports are an integral component for GA and provide nearby communities efficient access to local and regional markets. According to the U.S. Department of Transportation (2016), "these airports also accommodate flight training and have moderate activity from multi-engine propeller aircraft" (p. 7).

Basic airports fulfill the principal role of a community airport by serving the GA community and linking GA with the national airport system. U.S. Department of Transportation (2016) state “In some cases, a basic airport is the only way to access a community and provide emergency response access such as medical, fire, and mail delivery services” (p. 7). These airports have activity coming only from propeller aircraft and do not have jets using their facilities.

Unclassified airports tend to have minimal activity. U.S. Department of Transportation (2016) categories that out “of the 199 public-owned unclassified airports, 122 of these airports have up to three based aircraft and 78 of these airports have four to eight based aircraft" (p. 8).

UAS

In recent years, the use of UASs has been steadily increasing. From military to civil use, UASs have a place in today's demanding aviation industry. As the use of UASs increase, it is essential to regulate their use. When UASs are used for recreational activities such as aerial photography or video shooting, or when UASs are flown as hobby near a busy airport, there is a risk of the UAS flying in the path of departing or arriving flights. This can result in catastrophic consequences if not properly monitored.

UAS classification

Specific definitions of UASs change with organizations and their use. In general, UASs can be categorized in a variety of ways based on vehicle attributes including the type of aircraft (fixed wing or rotorcraft), flight altitude (high, medium, low), weight, and speed.

Different organizations such as North Atlantic Treaty Organization (NATO), Department of Defence (DoD), National Aeronautics and Space Administration (NASA), and State Regulatory Authority each have defined groups or classes of UAS. Fladeland, Schoenung, and Lord (2017) state that “most of these classifications are based on weight and altitude or speed” (p. 3). While classification group nomenclature differs among these organizations, some specific weight limits are commonly used. The typical weight limits for different classes of vehicles are 25 kg (55 lbs.), 150 kg (330 lbs.), and 600 kg (1320 lbs.).

Fladeland et al. (2017) mention that "the FAA has initially provided regulations (14 CFR Part 107) for "small UAS" operations for vehicles under 55 pounds, additional restrictions include a maximum speed of 87 knots and a maximum altitude of 400 feet" (p. 3). The 55-pound weight limit has also been historically used to define model aircraft in the U.S. Based on FAA interaction with other organizations concerning the integration of UASs into the NAS, it is expected that future FAA regulations will consider vehicle classes with weights from 55 to 330 pounds, 330 to1320 pounds, and greater than 1320 pounds.

Integration of UAS into the NAS

The FAA, since the very beginning, is responsible for regulating civil aviation and makes sure that adequate safety methods are put in practice. According to the National Academy of Sciences, Engineering, and Medicine (2018), "As means of ensuring that aviation operations are within acceptable levels of risk, the FAA, as regulator, generally requires the following three elements: A certified aircraft, a licensed pilot, and operational approval to access specific airspace" (p. 9). The requirements are the same for any UAS that operates in the National Airspace System. In addition to that, according to the federal regulations, any UAS that is flown for recreational purposes are considered according to the National Academy of Sciences, Engineering, and

Medicine (2018). Currently, there are five ways in which a UAS can legally operate in the NAS:

1) As per 14 Code of Federal Regulations (CFR) Part 101.41, any model aircraft that is flown for hobby or recreational use can be operated in the NAS if it strictly follows safety guidelines and other procedures under the advocacy of a community-based organization (eCFR — Code of Federal Regulations, n.d.a). In addition to that, the operation of the model aircraft should not interfere with and should always give way to manned aircraft with some operational limits. Certification of the aircraft or licensed pilots are not required, and no operational approval is needed to operate a model aircraft, but notification of ATC may be required.
2) In 2016, for small UAS rule compliant, the FAA published a summary of small unmanned aircraft rule (Part 107) which enabled UAS to be operated without the need for an airworthiness certificate. UAS can be operated for a hobby, recreational, commercial, public safety, or any other purpose in the National Airspace System, but mentions that the remote pilot in command must conduct a preflight check of the small UAS to ensure that it is in a safe condition for operation (FAA, 2016e). Other requirements include that person operating a small UAS must either hold a remote pilot airmen certificate

with small UAS rating or be under the direct supervision of a person who does hold a remote pilot certificate. Operational limitations (allowed to operate below 400 feet above ground level) and airspace where operations are permitted in the airspace (Class G) are mentioned in summary.

3) The 14 CFR 107.205 lists a number of provisions which including prohibition of operation from a moving vehicle or an aircraft, daytime only operations, requirement that the aircraft remains in visual line of sight, visual observer, operations of multiple small UAS by a single person, yielding the right way to manned aircrafts, prohibition of operation over people and operational limitations for small unmanned aircrafts (eCFR — Code of Federal Regulations, n.d.b). As mentioned in the previous paragraph, the airworthiness certificate may not be required, but the operator may need to adhere to additional operational limitations that are cited in the waiver application.

4) For Small UAS rule airspace authorization, 14 CFR 107.41, it is clearly stated the no person can operate an unmanned aircraft in Class B, Class C, Class D airspace or within lateral boundaries of the surface area of Class E airspace that is designated for an airport use (eCFR — Code of Federal Regulations, n.d.c) unless the person operating the UAS has proper authorization from the ATC.

5) The Air Traffic Organization generally issues the Certificate of Authorization (COA) or waiver to public sector operator (e.g., the military service, NASA, or public universities) for their given specific need and activity (FAA, 2018f). Once the organization applies, the FAA conducts a comprehensive operational and technical review. Upon review, additional restrictions may be given to the applicant for the safe operation of their UAS within other airspace users.

One of the primary contributing factors to the concept of risk assessment include vehicle and its system design (National Academy of Sciences, Engineering, and Medicine, 2018). This includes the operational risk associated with operating the UAS, area of operation, separation from manned aircraft, and human versus automation. For manned aircraft, assessment of risk is based on the probability of crew and passenger fatalities, but that is not the case with UAS operations, especially when integrated into the NAS. For a proper risk assessment of UAS operations, different variables need to be considered such as mission type, characteristics of the UAS, and other necessary environment variables. Out of the several areas that address the risk associated with UAS integration and in the context of safety risk management (SRM), the classification of the UAS and where it will predominantly operate must be described. Secondly, the hazards that are associated with operating and integrating UAS need to be identified.

An example of this is a lost link and failure to perform see and avoid. After the identification of the hazard, risk needs to be analyzed. Threats posed by UAS include harm to people on the ground or people in aircraft. The specific risks associated with such threats are unknown and poorly approximated. The risks luring from such threats need to be identified and mitigated. Mitigation techniques such as flight termination systems, geofences, and minimum-risk planning methods can be placed to enhance safety. Flight termination systems are electronic systems available on the UAS that are capable of ending the UAS's flight in a very controlled manner. Geofence on a UAS is a virtual geographic barrier that is created for the UAS that controls the areas on which the UAS can operate.

One of the first aspects of integrating UAS into the NAS is how ATC will handle the presence of UAS activity in controlled airspace. Kamienski and Semanek (2015) state that the main difference between a UAS and manned aircraft is the remote location of the pilot operating the UAS. Instead of being onboard, the pilot is in a different place that may or may not be near the current location of the UAS. The majority of such UAS platforms operate in G Class airspace and have a wide variety of use, for example, transmission line inspection, real estate application, law enforcement, etc.

As mentioned before, the NAS is divided into several different classes of airspaces. Currently, large UAS operations take place in Class A airspace. There is a need for adequate regulation because aircrafts flying in the NAS are required to see-and-avoid other aircraft. A pilot may be remotely located when operating a UAS making it impossible to fulfill a see-and-avoid, especially if flying in the NAS. However, when aircraft are flying in Class A airspace, ATC provides them with positive separation from other aircraft. This means that UAS lack of ability to see-and-avoid other aircraft is not a major issue in Class A airspace (Kamienski & Semanek, 2015). Congestion is another issue in the NAS, but congestion widely varies from region to region, and UAS operations generally take place in the uncongested region, which minimizes their impact on ATC.

Kamienski and Semanek (2015) suggest that while UAS operations are expected to change soon, the NAS will not remain the same. Also, if the UAS is capable of meeting the airspace equipage requirement, it could fly in areas with manned aircraft. Furthermore, the UAS operate in different ways than manned aircraft. So it is essential for ATC to have all the information specific to the UAS types and missions while flying in that airspace sector. All this information can be provided through automation, briefings, training, reference manuals, or other methods. Kamienski and Semanek discuss the need to proceduralize the prioritization of UAS missions in the NAS versus other NAS activities.

Clothier, Williams, and Washington (2015) developed a safety structure for UAS operations near a populated area using a barrier bow-tie model. In the case study, a remotely piloted aircraft system was operated in a university field accessible to students and members of the public but not fully utilized. After the selection of a site for the case study test, barriers were implemented as a way to mitigate risk. Barriers consist of the pre-flight checklist, system reliability barrier, tactical terrain awareness barrier, failure recovery barrier, strategic terrain awareness barrier, and impact barrier were implemented in the barrier bow-tie model (BBT). From the evaluation using the BBT model, they were able to develop a framework that provides a systematic means for evaluating all the controls, which are not just limited to the technical airworthiness of the system. The framework that is developed in the study is not only useful in understanding operational safety cases but also helpful in developing safety regulations for a safe UAS operation.

In addition to developing a safety framework and a formal framework for integration of the UAS into the NAS, regulations are also needed to implement a developed framework. The NAS, as mentioned in the previous paragraph, is in place to ensure the safety of aircraft that fly through it, but with an increase in traffic, the FAA estimates that air traffic will increase one percent per year for the next 21 years making it necessary to make NAS regulations more stringent (Maddox & Stuckenberg, 2015).

With UASs having an increasing presence, Congress passed the FAA Modernization and Reform Act of 2012 to improve aviation safety and capacity (Maddox and Stuckenberg, 2015). The Act also instructs the government to develop a comprehensive plan to safely accelerate the integration of the civil UAS into the NAS. Maddox and Stuckenberg state that drone integration is problematic due to its regulatory impediments to their operations and the resulting political climate. All UASs are restricted to below 400 feet above ground level or Special Uses Airspace. These restrictions are in place because of the hazards these drones might pose to manned aircraft and the public.

Despite the implementation of regulatory measures, inadequate safety systems have slowed down the integration of the UAS into the NAS. Particularly, three technological aspects have been the forerunners for challenging the integration of UAS consisting of sense and avoid system (SAA), control and communication link, and general UAS safety (Maddox & Stuckenberg, 2015).

In 2014, an American Airlines group regional jet in Florida nearly collided with a drone at 2,300 feet (Maddox & Stuckenberg, 2015). The operating limit for a drone is 400 feet off the surface. A collision at 2,300 feet would have resulted in severe consequences. This particular incident underscores the need for SAA and highlights the need to make the operation of UAS in NAS safer.

According to the International Civil Aviation Organization (2011),

> A key factor in safely integrating UAS in non-segregated airspace will be their ability to act and respond as manned aircraft do. Much of this ability will be subject to technology that provides the ability of the aircraft to be controlled by the remote pilot and to act as a communications relay between the remote pilot and ATC (p. 5).

The technology must also have a high degree of performance such as transaction time and continuity of the communications link as well as the timeliness of the aircraft's response to ATC instructions. This still leaves the question of how to integrate UAS into the NAS. Integration may result in significant provocative changes or the addition of new regulations, legislation, and technological issues. Amongst these, most significant obstacles are inadequate safety systems, inadequate statute, and incomplete threat analyses. Current criminal, civil, and regulatory provisions are inadequate for efficient determination of hazardous use of UAS.

Integration of UAS at Airports

For the integration of UAS into airports, we have to keep in mind that each airport is unique in terms of operation and its layout. Similar is the case with UAS; each one is unique in terms of their operational capabilities (Neubauer, Fleet, Grosoli, Verstynen, 2015). Therefore, it is necessary to analyze each system separately keeping in mind their size, performance, operational qualification, operating procedures, and emergency profiles/procedures. Over the last couple of years, airports have started bringing UAS business and operations to their facilities. After initial operations at civilian as well as military airports, it was suggested by Neubauer et al. that "in many ways unmanned aircraft can be treated just like manned aircrafts" (p. 11).

Killen-Fort Hood Regional Airport (GRK), in addition to being a military airport, has 26 daily commercial flight, and also has two UAS flying into the airport at least four days a week (Neubauer et al., 2015). For safe operations of UAS at its facility, GRK has taken steps such as airline-UAS schedule deconfliction where the UAS is operating out of GRK use notice to airmen (NOTAM) to keep other flying parties and airlines operating out of the airport of any UAS operations. Lost link loiter point planning is done in such a way that it does not interfere with the airport's traffic term and is usually selected over a non-populated area. Another valuable lesson that can be learned from UAS operations at GRK is training. Many ground operations personnel may not have an aviation background, and although fully versed with safety practice for manned aircraft, they might not be fully aware of additional safety procedures needed when a UAS is using the same facility as a manned aircraft. Stark Aerospace Similar to steps taken at GRK, Golden Triangle Airport (GTR) in Lowndes County, Mississipi, in order to ensure safe operations of UAS at its facility, has placed communications antenna to make sure that there is adequate line-of-sight ground communication when a UAS is taxiing. At GRK, the UAS is primarily operated by the military for their routine operations like flight testing while UAS operations at GTR are primarily carried out with Israeli Aerospace Industries (IAI) Heron Aircraft by Stark Aerospace which is a defense contractor specializing in UAS use for military operations.

The same steps as taken for UAS integration into NAS must be taken for integration at airports. According to Neubauer et al. (2015), “the introduction of UAS operations, in most cases, will represent a system change to an airport. This change to the system is not ordinary and may require some distinctly different ways in which aircrafts are operated” (p. 45). After a change has been introduced in the system, the next step is to initiate a safety risk assessment (SRA) to identify anticipated hazards and assess the associated risk that will eventually help the airport and the UAS operator. The process for the assessing system change risk is the same process used for UAS integration into NAS. This process is to define the system, which identifies the element and the stakeholders where the UAS will be operating. The next step is the identification of hazards due to the operation of UAS at an airport, after the identification of hazards, risks associated with the hazards need to be analyzed. Once the risks are identified, the next step is to assess the risk which means that the risk is defined by their severity and likelihood. A combination of severity and likelihood provides the level of risk. After the risk is assessed, the final step is to take steps and put controls to mitigate the risk to an acceptable level. It is essential to know that the threats that may arise due to UAS operations in the NAS and airports largely depends upon the type of operations, the category of the UAS, and availability of adequate standard operating procedures (SOP). UAS has already started taking their place in the aviation industry but still must go through a myriad of challenges in the forms of tests, risk and hazard assessment, risk analyses, innovations, improvements, regulations, and legislation to see themselves properly integrate into the NAS and airports.

Bow-tie Method

The bow-tie method did not develop on its own. Four historical developments in risk assessment preceded bow-tie. They are as follows: Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Cause Consequence Diagram, and Barrier Thinking (De Ruijter & Guldenmund, 2016). Risk analysis is a proper systematic approach that involves both qualitative and quantitative information integrated that provides information on potential causes, consequences, and likelihood of adverse events (Ferdous, Khan, Sadiq, Amyotte, & Veitch, 2013). The likelihood for any event can be referred to as a quantitative measure of an occurrence expressed by frequency or probability of when an event can happen. A bow-tie diagram, as aforementioned, comprises of FTA and ETA. These two methods are one of the most common methods used from a risk analysis perspective. Ferdous et al. (2013) mention that FTA develops a graphical interpretation that explores the relationship between causes and occurrences for any undesired event. This event is generally termed as a *top event.* ETA, like FTA, develops a graphical model of consequences that consider the undesired event as an initiating event, and from that identifies possible outcomes from that particular event.

Both FTA and ETA investigate the cause and its subsequent consequence of an event for a system. A bow-tie diagram, also a visual tool, made up of both FTA and ETA on the left and right side of the diagram representing the risk control parameters such as causes, consequences, and threats (Ferdous et al., 2013). The quantitative analysis of a bow-tie diagram determines the *likelihood* of the undesired event as well as the outcome.

Typically, when the bow-tie method is used, it first starts with an FTA, where potential incidents are identified, essentially analyzing necessary pre-conditions. In the next step, ETA occurs in the opposite direction to identify the chain of events between the occurrences of the incident and any final undesired consequence (Targoutzidis, 2010). Once these two steps are completed, the next step is to identify safety barriers. Safety barriers are identified in both directions, before the incident, and after the incident either to prevent the incident from developing into an accident or to prevent it from happening at all.

History

The Royal Dutch/Shell group first developed the bow-tie concept. Acfield and Weaver (2012) state that “It was intended to provide the user a means by which risk information could be provided graphically" (p. 6). The name bow-tie comes from the diagram once completed resembling the shape of a bow-tie as shown in Figure 4. Over the years, many industries such as Oil and Gas exploration and production, chemical processing, defense and security, shipping, packing and logistics, medical, mining, and aviation have started using bow-tie as a method to understand and evaluate risk.

Components of Bow-tie Diagram

Every bow-tie has a single hazard and a top event. For the top event, threats associated with it and their subsequent consequences are pictorially represented. In a bow-tie, the term hazard is defined as an activity such as an aircraft flying and a top event is an event such as an engine failure. The top event in a bow-tie is a direct result of a hazard. To justify the use of these definitions, when an aircraft is flying, it is a potential hazard where many undesired events can occur. For example, an engine failure or turbulence is an undesired event that can occur and lead to unwanted consequences. Therefore, there can be multiple bow-ties for a hazard with several top events.

After the identification of the hazard and the top event, the next step is the identification of threats. In a bow-tie, threats can be internal as external.

After the identification of threats, consequences are identified. Consequences can be defined as an outcome that is, in any way, related to the top event (Acfield & Weaver, 2012). Once all the associated hazards and top events for a case are identified, the level of risk associated with that particular top event can be evaluated. Once the threats and the consequences are defined, the next step in a bow-tie is to define barriers. Barriers, in general, can be defined as a *fence* or an obstacle that prevents movement or progress, or access. Keeping in mind, the context that we are using, the barrier can be defined as a preventive measure that can be implemented in a system to mitigate the effects of a threat or a consequence occurring due to the top event.

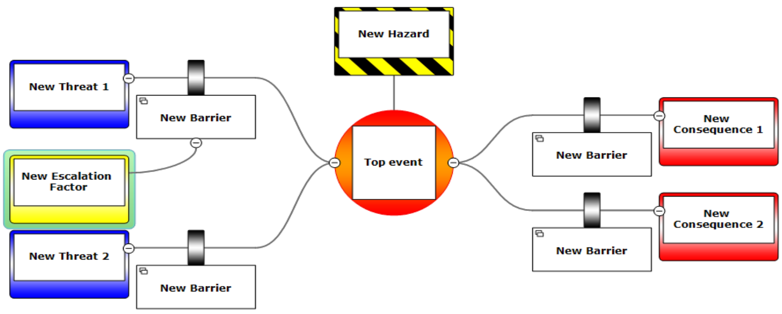

Figure 4: Components of a Bow-Tie Diagram.

Hollnagel (2008) suggests that the best way to ensure the state of safety is either to prevent something from happening or to protect its consequence. Because it is impossible to prevent unwanted events or eliminate risks, these two approaches are best if used together. In doing so, the two primary types of responses, prevention, and protection involve the use of a barrier. When considering different types of barriers, there are several types of barriers that can be used and depend on the type of risk assessment. Examples of barriers include Social barriers, Organizational barriers, Hardware barriers, Cultural barriers, Behavioral barriers, and Human barriers. Once barriers are identified, the next step is to identify what these barriers are and what they do. The function of a barrier is described as the modes or way in which it is possible to prevent or to protect against any unwanted or uncontrolled propagation of information (Hollnagel, 2008). After the identification of the barrier, escalation factors are identified. Denny and Pai (2016) describe escalation factors as any weakness or vulnerabilities that can lead to a breach in the barrier. Escalation factors can also act as a failure mode for a specific barrier that has been implemented on the barrier. It is also the sequence of threats which can be lead to the top event. Figure 4 shows what a basic bow-tie diagram looks like. The barrier systems describe how the barrier functions are carried out. Four barrier systems can be identified and discussed in Table 1.

A principal advantage of using bow-tie is that it provides a proper, easy to understand visual representation of risk, which not only includes each applicable element, but also the relationship that exists between them. It also identifies areas of concern such as inadequately controlled threats or consequences for further treatment and study. Acfield and Weaver (2012) state that visualization of the interactions between risk elements allows the representation to be more readily comprehended and understood because most individuals are not experts in the area of risk and but instead experts in the applicable subject matter (e.g., ATC). This is crucial if risk management is to be an activity undertaken by those who are accountable for safety rather than being outsourced to a safety department.

Table 1.

Barrier system

Barrier System	Barrier Function	Example
Physical	The primary function of the barrier is to contain or protect. This barrier is mostly a physical entity.	Safety belts or harnesses, fences, filters, etc.
Functional	The main function of this barrier system is to prevent movements or activities.	Distance, persistance, pre-conditions, synchronization, etc.
Symbolic	The main function of this barrier is to counter or prevent actions.	Demarkations, labels & warnings, clearance, approval, etc.
Incorporeal	The primary function of this barrier is to comply or conform to rules, guidelines, or regulations	Rules and regulations, SOPs, etc

Note. Adapted from "Risk + barriers = safety?", by Hollangel, E., 2008, *Safety Science*, *46*, p. 224.

Bow-tie in Healthcare

As mentioned in previous paragraphs, bow-tie finds its use in many industries, for example, in healthcare. Mcleod and Bowie (2018) mention several examples where bow-tie has been used to evaluate risk assessment. Bow-tie analysis has been previously used to assess the risk associated with critical events in intensive care units. In this particular case, nine different bow-ties were generated covering three hazardous situations. In that analysis, there have been 84 barriers identified that were not implemented and led to 37 recommendations for improvements. Concerning the barriers that were missing, it was determined that these barriers were never considered when protocols were composed.

Bow-tie in Oil & Gas Industry

Bhopal gas tragedy was one of the worst gas industry disasters. Vaughen and Kenneth (2016) used the bow-tie diagram in addition to process hazard analysis to see which preventive measures could have been taken at the facility where the tragedy took place. In the paper, process hazard analysis (PHA) was combined with a bow-tie diagram to illustrate barriers that could have been placed in order to prevent leakage.

Bow-tie in Aviation

Recently bow-tie has also found its use in the aviation industry especially when it comes to safety. Cui, Zhang, Ren, and Chen (2018) have developed a new aviation safety index and its solution under uncertainty condition using the bow-tie model. The bow-tie model is broken down into the following steps:

- The top event of the FTA is the initial event of the FTA, and it is the critical event of the model as well.
- The fault tree and event tree are connected by the common critical event.
- All the same accident causations and basic events are located to the left of the model.
- The accident consequences are located to the right of the model.

- All the branches in the left always gather to the critical event, and in the right, all the consequence are extended from the critical event.

Once a proper procedure was set, Cui, Zhang, Ren, and Chen (2018) takes an aviation-based scenario, maps it onto a bow-tie diagram and then introduces the Monte-Carlo computational method, a computerized mathematical technique that allows researchers to account for risk in quantitative analysis and decision making, and generates an aviation safety index. From the bow-tie diagram and the computational results, the proposed aviation safety index can describe the aircraft safety and evaluate the influence of uncertainty of different factors in aviation actions and is more direct than traditional safety indexes.

The bow-tie model has also been used to research on a controlled flight into terrain risk (CFIT) analysis (Wang, Wan, and Miao, 2018). CFIT flights generally occur under instrument meteorological conditions (IMC), flight at night, or both conditions under deplorable visibility conditions. A primary reason attributed to the pilot's lack of environmental awareness concerning the aircraft's vertical and horizontal position relative to the ground, surface, or any other object. Wang et al. (2018) state that the loss of situational awareness is the leading cause of CFIT accidents. From the results, and after the completion of the bow-tie diagram the data obtained was crucial in pointing which factors played a hand in CFIT. Other factors such as Ground proximity warning system GPWS warning, high approach speed, deviation, of course, deviation of glide, landing and descent rate of non-landing configuration also played a role in CFIT, particularly, at airports.

Content Analysis

For the analysis in the current study, content analysis will be performed. The study methodology will be described in Chapter 3. However, it is briefly explained in this section. According to Krippendorf (2004), "Content Analysis is a research technique for making replicable and valid inferences from texts (or other meaningful matter) to the context of their use" (p. 18). Elo and Kyngäsh (2008) state that content analysis can be used as a method of analyzing documents and allows the researcher to test theoretical issues that help understand the data, and most importantly, according to Elo and Kyngäsh, "Content analysis as a research method is a systematic and objective means of describing and quantifying phenomena" (p. 108). One of the main aims of content analysis is to attain a concise and broad description of the phenomenon. The outcome from the content analysis is categories or concepts that help the researcher come up with a model or a conceptual system. According to Okumus and Kevin (2007), "It can provide rich and in-depth accounts on a wide range of topics. It establishes categories and then counts the number of related words, sentences and issues under each category" (p. 81).

When data is collected, the primary purpose of data analysis is to organize and elicit meaning from the collected data and present realistic conclusions (Bengtsson, 2016). One of the reasons for selecting qualitative content analysis is that the method, from the data, presents the findings in words or themes which in turn helps the researcher in drawing necessary interpretations of the results.

Chapter 3

Methodology

Introduction

This chapter presents the methodology for the current study. It provides information on the research design, approach used for the design, data collection, instrumentation and materials, and data analysis.

As the use of UAS has steadily increased, there is a necessity to evaluate the associated hazards and risks. The data collected for this study is from the ASRS and NTSB reports from two aviation incidents, and accidents report portals. This research addresses the problem of identifying any risk and barriers that can be used as a defense to mitigate the risk to an acceptable level with the integration of UAS into the NAS and airports

Research Design. The research design used for the study is qualitative content analysis. One of the primary purposes of using qualitative content analysis is that archival data from two primary UAS incidents and accidents report databases have been used for this study. The reason for selecting archival data is that the information selected from the reports are accurate to its form and do not have an anomaly. If interviews or surveys were instead used to collect information, the questions would have focused on errors or mistakes done by the participants when operating UASs. However, participants might not be truthful in their responses leading to inaccurate results and limited generalizability of the study findings. The approach of the design is instead in the development of themes using content analysis through analyzing reports.

Each report was thoroughly analyzed, and contributing factors reported. Once the contributing factors from each report were collected, the contributing factors were grouped into categories from the most frequently occurring contributing factors and probable cause(s) displayed in the bow-tie diagram. One of the main advantages of using bow-tie diagrams is that it is a visual tool in representing risks associated with the integration of UAS in the NAS and airports. It assists in displaying barriers that reduce the risk to an acceptable level.

Research methodology. The purpose of the study was to utilize a qualitative content analysis. The qualitative research component for this research study utilized archival data found in ASRS and NTSB reports aviation incidents and accidents report portals. Access to this archival data was publicly available through the ASRS and NTSB websites. There are advantages and disadvantages in selecting a content analysis. According to Vitouladiti (2014), the advantages of content analysis are:

- Useful to study written document, graphics, and videos.
- Widely used and understood as a research methodology.
- Helps in understanding trends exhibited by a group or collection of documents.
- Useful for analyzing archival material and documents.
- It is easily repeated or changed if a problem arises.
- Establishes reliability and is easy and straightforward.

- Of all the other research methods, content analysis is the easiest to replicate as the materials used for any previous studies can be made readily available.

There are also disadvantages of using a content analysis that consist of:

- Content analysis is a purely descriptive method describing what is out there and does not point to the underlying cause of the observed trend or pattern.
- The reach of the analysis is limited to the material used for data collection.

Data collection. The first step conducted after the committee approval and Institutional Review Board (IRB) approval was to collect data on UAS incidents and accidents reports from the ASRS and NTSB Aviation Accident Database and Synopses. Then, the data was coded and recoded using the instrument in Appendix A and Appendix B respectively. Data categories analyzed within the reports consisted of the flight phase, airspace class, flight conditions, summary of the event, and contributing factors from the ASRS reports. For the NTSB reports, the data categories analyzed were the narrative analysis and probable cause and findings. For the ASRS reports, the data categories analyzed were flight plan, flight phase, flight conditions, airspace class, event, and contributing factor.

Bengstton (2016) states that "Content analysis can be used on all types of written text no matter where the material came from" (p. 10). Ison (2018) states that content analysis is used as a method to uncover common information in the literature. This particularly bodes well with the need for the current study because, from the reports and records that were garnered from the website, common information was filtered out that was an indication of a contributing factor or the primary cause of the UAS incidents and accidents.

The ASRS website provides a user friendly interface where the user can look at incidents and accidents depending on various categories such as model of aircraft, date range, location, environment, and event assessment wherein the user can look up different types of event type, for example, airspace violations, aircraft equipment problem, ATC issue, etc. For data collection, UAS incidents and accidents reports were searched on from January 2008 to January 2018. Under the aircraft model, the unpiloted aerial vehicle was selected. After the information mentioned above was inputted into the search criteria, the search was carried out. From the search, a total of 108 records were generated. The records were then exported into an excel file for further examination.

A similar procedure was utilized for collecting data from the NTSB website. On the NTSB website, the aviation accident online database was accessed. Then, the January 2008 to January 2018 date range was selected for the search. One of the limitations on the website was that there was no option available to select only reports with UAS, UAV, and drone as the aircraft make/model. Instead, the event detail section was selected, and a specific word string was entered consisting of UAS, UAV, and drone in both singular and plural forms to generate all reports that contained one or more of these terms. In total, six searches were carried out, and after careful examination of the generated reports, it was found that half of the reports were without information about UAS accidents and incidents. In order to get the most accurate data from the reports, each report was carefully analyzed regarding the nature of the narrative. Reports without information regarding UAS incidents and accidents were discarded. After discarding all the unnecessary reports, there were 18 NTSB reports identified bringing the total number of combined ASRS and NTSB reports to 126 reports.

Instrumentation and Materials

Instruments. To investigate and analyze data, this research employed a quantitative data collection instrument. Data collection for this methodology utilized the content analysis instrument forms located in Appendix A and B. Appendix A has the instrument for ASRS and Appendix B for NTSB. The data collected consisted of the flight phase, airspace class, flight conditions, summary of the event, and contributing factors for ASRS reports. The data collected consisted of narrative analysis and probable cause and findings for the NTSB reports.

Materials. Two types of reports were used for data collection. The reports from the ASRS consisted of technical as well as regulatory aspects of the UAS incidents and accidents. The reports from the NTSB consisted of a brief narrative of the incidents and accidents and listed the probable cause and findings for the reported incidents and accidents.

BowTieXP (CGE Risk Management Solutions, n.d.) software was used as a tool for a visual representation to display the data. Different bow-tie diagrams were created based on contributing factors identified from the two portals. The bow-tie diagrams display and identify barriers. The barriers were brainstormed for each threat identified from the contributing factors and are in the bow-tie diagram. Once the barriers were identified, the software displayed the escalation factors for each identified barrier. Escalation factors as mentioned in Chapter 2 are defined as any deficiencies or loopholes that could lead to a barrier failure. After integration of the threats and consequences, the software tool provided a display of the risks associated with the integration of UAS into the NAS and at airports. Contributing factors and probable cause(s) were identified from the reports and were incorporated into individual bow-tie diagrams to provide multiple diagrams for each contributing factors and probable cause(s).

Data Analysis

The next step after relevant reports were identified was to begin the content analysis.

Content analysis, as given by Bernard, Wutich, and Ryan (2017), can be carried out by the following steps:

- Devise a research question and corresponding hypothesis, which is based on an existing theory or prior research.
- Select a set of texts to test the question or hypothesis.
- Create a set of codes comprised of variables and themes in the research question or hypothesis.

- Pretest the variable on a few of the selected texts. After the pretest is carried out, any problems that arise about codes and the coding needs to be made consistent for the entire process of coding.
- Apply the code to the text (p. 245).

The next step is to select relevant text from the reports to identify the unit of analysis. Unit of analysis refers to the part of the selected text, document or other relevant data will be coded to analyzed (Bernard, Wutich, and Ryan, 2017).

This same technique was used for the analysis of the UAS incidents and accidents reports. The majority of the reports, in their format, had a contributing factor and probable cause section where the issuing organizations mentioned the reasons why the incidents and accidents had occurred. From this section, contributing factors and probable causes were used for the next step, i.e., to create a set of codes. For the current study, the code will be the categories that were created in the instrument form. One key advantage of using this procedure was that it brings to light which contributing factors and probable cause(s) have a high frequency of occurrence and ensures that whatever pattern or sequence of events found in the reports can be generalized.

The third step is coding. Coding is nothing but a short phrase or a summary that is picked from the report or the selected document. For the current study, different themes were created by using the HFACS to code contributing factors and probable cause(s). The HFACS categories are divided into four main categories: Organizational Influences, Unsafe Supervision, Preconditions for Unsafe Acts, and Unsafe Acts and the four categories and their sub-categories are displayed in Figure 5 (Shappell & Wiegmann, 2000). These categories and sub-categories provide in-depth information on particular deficiencies in an organization and are discussed below:

1. Organizational influence:
    a. Organizational Climate (OC): OC looks at the overall running of the organization. Things such as organization policies, command structure, and organization climate fall under this category.
    b. Operational Process (OP): OP analyses the process by which an organization carries out its day-to-day operations.
    c. Resource Management (RM): RM describes how the organization uses its resources such as workforce, finances, and equipment that aid in their day-to-day operations.
2. Unsafe Supervision:
    a. Inadequate supervision (IS): IS analyses oversight in the management of organization personnel among other resources.

b. Planned Inappropriate Operations (PIO): PIO looks into the management and assignment of work that includes but is not limited to risk management and crew pairing.
c. Failed to Correct Known Problems (FCP): FCP looks into a deficiency identified in an organization, but no adequate corrective measures are taken to rectify any identified deficiency.
d. Supervisory Violations (SV): Any existing rules and regulations, instructions, the standard operating procedure that is disregarded or not taken seriously fall under SV.

3. Preconditions for Unsafe Acts:
    a. Environmental Factors:
        I. Technological Environment (TE): TE includes issues that are related to the design of equipment, user interface, checklist layout, and automation.
        II. Physical Environment (PhyE): PhyE highlights the operational setting such as the weather, altitude, terrain, and other environmental condition such as heat during the operation is carried out.

    b. Condition of Operator:

I. Adverse Mental States (AMS): AMS looks into the psychological or mental conditions that affect performance such as mental fatigue, misplaced motivation, and anxiety.

II. Adverse Physiological States (APS): APS is medical and physiological conditions that affect performance such as illness, intoxication, medical condition, etc.

III. Physical/Mental Limitations (PML): PML highlights permanent physical or mental disabilities that can affect performance such as poor vision, low physical strength to complete an assigned task, and other mental illnesses.

IV. Personnel Factors Communication, Coordination, & Planning (CC): CC includes communication, coordination and teamwork issues that harm performance.

V. Fitness for Duty (PR): PR includes crew rest periods, alcohol restrictions, and other off-duty restrictions.

4. Unsafe Acts:

   a. Errors

      I. Decision Errors (DE): DE looks into the errors that occur as part conscious and goal-intended behavior but may prove to be inadequate for the situation in which it is used. These errors generally arise due to poorly executed procedures, improper choices, or a misunderstanding of available information.

II. Skill-Based Errors (SBE): SBE are any highly practiced behavior that usually occurs with little to no conscious thought. These errors generally occur in unintentional deactivation of switches, elapsed intentions, or omitted items from the checklist.

III. Perceptual Errors (PE): PE are errors that arise when the personnel's sensory input is degraded, for example, when flying in the dark, poor weather conditions or poor visibility conditions. These errors generally result in misjudgment from the crew.

b. Violations:

I. Routine Violations (RV): RV focuses on violations that happen to be habitual by nature. These errors generally arise when the management of the organization allows violations from the established rules and regulation to occur.

II. Exceptional Violations (EV): EV are violations that are neither typical of the personnel nor condoned by the management.

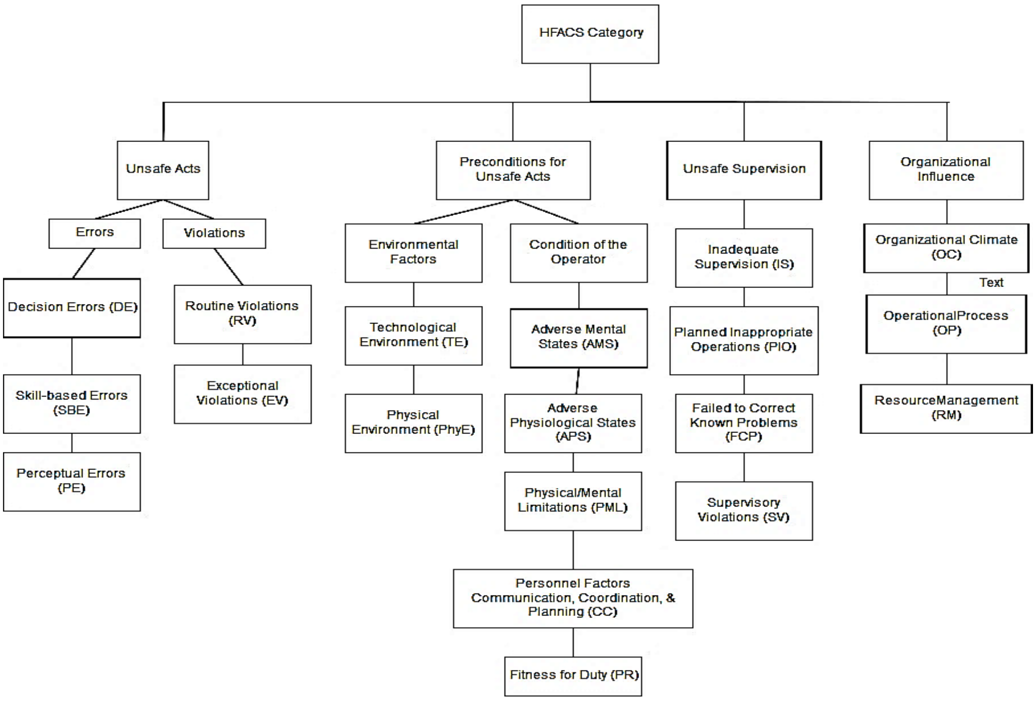

Figure 5: HFACS Categories and Sub-Categories (Adapted from Shappell & Wiegmann, 2000)

Some of the themes that can be used to identify the HFACS category include mechanical failure, human factors, airspace violation, etc. These categories act as themes for the code. Once the themes are set, individual contributing factors and probable cause(s) can be filtered to their respective themes. This procedure was first used for reports from January 2008 to January 2013. After setting up the theme, reports were again carefully analyzed, and contributing factors and probable cause(s) were sorted out based on their theme.

For pre-testing of variables, the reports were analyzed as part of creating codes for consistency in the coding process in terms of filtering contributing factors and probable cause(s) according to the themes. This was done by selecting reports from January 2014 to January 2015, which were not part of reports used to develop the code. The same procedure was used to create themes from the validation years. Once themes were developed, they were cross-checked with themes from original reports to make sure that there was adequate consistency in the process of coding. The coding process took around 10 days to complete.

Once the coding procedure was made consistent with the themes for the contributing factor and probable cause categorization, the next step was to implement the derived procedure for reports from January 2008 to January 2018.

The final step was to create the bow-tie diagrams. After the categories were created from the reports and relevant contributing factors and probable cause(s) were sorted out, the final analysis was carried out to form bow-tie diagrams. Per the first research question, the contributing factors or probable cause risks were identified from the bow-tie diagrams. This was done for each identified category. Once the risks were identified from the bow-tie diagram, the second research question was answered by brainstorming adequate and relevant barriers in the bow-tie diagram, which will act as a control towards the threat and will mitigate the risk.

Summary

In order to conduct the current study, qualitative content analysis was used as the research methodology. The main reason for using qualitative content analysis was to develop themes from the data collected from the ASRS and NTSB reports. The ASRS and NTSB portal steps were discussed in this chapter that describes how the reports were collected. Once, all the available reports were collected, two instrument forms were developed, one for the ASRS reports and one for the NTSB reports. The data contained in these reports were used to develop themes to determine the most frequently recurring contributing factor and probable cause(s) for UAS accidents and incidents identified in the reports. Once these themes were developed, the next step was to include them in the bow-tie diagrams. The bow-tie diagrams are visual tools in understanding the threats and consequences that are associated with UAS integration. From the identified threats and consequences, the software assists in the identification of barriers to bring the level of risk to an acceptable level.

Chapter 4

Results

Introduction

The purpose of this study was to determine the risks that are associated with integrating UAS in the NAS and airports. The methodology for this study consisted of using qualitative content analysis to identify the HFACS category for the most frequently occurring contributing factor and probable cause(s) for UAS incidents and accidents that were reported in the ASRS and NTSB database.

Data Analysis

NTSB and ASRS reports were analyzed to identify discrepancies that needed to be discarded. Discrepancies consisted of reports that did not have information relevant to UAS incidents or accidents. Next, the unit of analysis was defined which referred to the parts of a text or other relevant data that were coded and analyzed (Bernard, Wutich, and Ryan, 2017). This unit can be a single word, sentence, paragraph, or whole document (Zhang & Wildermuth, n.d.). The unit of analysis selected for the current study was a complete report from the NTSB and ASRS database. The next step consisted of creating a set of codes. The set of codes were included in the instrument form. Due to the difference in the format of the NTSB and ASRS reports, two different set of codes were developed based on the research question and the data available in the reports. The NTSB reports were coded based on the narrative analysis, probable cause(s), and findings. The ASRS reports were coded based on the flight conditions, flight plan, flight phase, airspace class, and contributing factors. For the pre-test of the set of codes, a total of five reports from NTSB and ASRS were selected. The information that was available from these five reports were included in their respective instrument forms. Once the data collection was completed for the pre-test, the instrument forms were analyzed to ensure that the necessary information was being collected. After the initial analysis, the instrument forms were recoded to include more variables such as the contributing factors, and HFACS category and subcategory. The information regarding the reasoning behind the addition of more variables on the instrument form is provided in the next section. The four HFACS main categories were listed in the instrument form as provided by Shappell and Wiegmann (2000). It was determined during the pre-test that the reports needed to be analyzed at the HFACS sub-category level in order to better identify the contributing factors of the incident and accident.

After the pre-test of coding the reports, HFACS sub-categories were added to the instrument forms to ensure complete analysis of information extracted from the reports. After this change was finalized, the NTSB and ASRS reports were thoroughly analyzed using the instrument forms. Each report was carefully studied to look for the information that could fit in their respective instrument forms. A detailed analysis using the instrument forms was conducted to determine the HFACS category of the most frequently occurring contributing factor leading to UAS incidents and accidents. Table 2 displays a summary of the results showing the number of reports identified within different HFACS category and sub-category. For the NTSB reports, OP and TE were most frequently occurring HFACS sub-category. For the ASRS reports, TE, SBE, and EV were the most frequently occurring sub-category.

Table 2

Number of NTSB and ASRS Reports with HFACS Category

HFACS Category	Number of NTSB Reports	Number of ASRS Reports
Organizational Influence		
OC	2	2
OP	6	4
RM	0	0
Unsafe Supervision		
IS	1	9
PIO	0	1
FCP	0	13
SV	0	1
Preconditions of Unsafe Acts		
TE	4	20
PhyE	2	4
AMS	1	3
APS	0	0
PML	0	0
CC	0	9
PR	0	0
Unsafe Acts		
DE	0	10
SBE	1	20
PE	2	1
RV	0	2
EV	1	21
HFACS Category N/A	0	4

A detailed description of the data analysis for the NTSB and ASRS reports is contained in the next two sections of this chapter.

NTSB Data Analysis

After the pre-test of the NTSB instrument form, the instrument was re-coded to include aircraft issues, personnel issues, and environmental issues in addition to the HFACS categories and sub-categories. During the pre-test, it was also found that two reports were repeated twice and thrice respectively, but with different accident numbers. Each report had information that was not provided in the alternate versions of the report, and therefore all the reports about the same accident were analyzed as if it was all part of the same report to eliminate the repetition. This brought the total number of NTSB reports to 12 reports analyzed using the NTSB instrument form. During the analysis, it was found that three reports suggested that aircraft issues were not connected with the cause of the incident or accident, seven reports suggested that environmental issues did not have a role in the incident or accident, and three reports suggested that personnel issues did not have a role in the incident or accident as shown in Table 3. After eliminating all the factors that did not have a role in the incident or accident, the next step was to categorize according to the HFACS category or sub-category of the contributing factors and probable cause(s) of the incident or accident. To identify the HFACS category, all the listed causes and contributing factors were extracted from the reports and listed on the instrument forms. After all the relevant data was compiled and the final analysis was complete, there were eight accounts of organizational influences as the HFACS category for contributing factors and probable cause(s). Preconditions for unsafe acts were identified six times, unsafe acts were identified four times, and unsafe supervision was identified two times. A summary of findings from the NTSB reports is included in Table 2 From the final analysis, and it was concluded that organizational influence was the most frequently recurring HFACS category for contributing factors and probable causes of the incidents or accidents. After identifying the most frequently occurring HFACS category, the next step was to identify the sub-category under the organizational influence. From further analysis of reports, six accounts of OP and two accounts of OC were found. After the completion of data analysis for the NTSB reports, it was found that organizational influence had a significant role in the contributing factor and probable cause(s) for the incidents or the accidents, and OP was recognized as the most frequently occurring sub-category under the organizational influence.

Table 3

NTSB Data Analysis Summary

	Number of NTSB Reports	
Data Categories	With	Without
Aircraft Issues	9	3
Personnel Issues	9	3
Environmental Issues	5	7

ASRS Data Analysis

For the ASRS data analysis, the instrument form for data collection is provided in Appendix A. After pre-testing of codes, it was found that not all relevant data was being extracted from the reports. Therefore, contributing factors, flight conditions, and event categories were added to the instrument form after the pre-test. The new instrument form was used to collect data from all of the available reports from the ASRS database after the re-coding. During the analysis, it was found that VMC conditions prevailed during UAS incidents or accidents. In addition to the available flight condition information in the reports, it was found that 37 reports had no information available for flight conditions. A summary of flight condition data is presented in Table 4. Five reports had identified IMC flight conditions while only two reports identified mixed flight condition.

Table 4

ASRS Flight Condition Data Summary

Instrument Form Categories	Number of Reports
Flight Conditions	
Mixed	2
IMC	5
VMC	64
None	0
N/A	37

From the analysis of flight plan data, it was found that IFR was identified in 38 reports while VFR was identified in only eight reports. Summary of flight plan data analysis is provided in Table 5. There were 38 reports were identified with no flight plan for their flights, and 25 reports had no information available regarding the flight plan. The reason so many reports had no flight plan for their operation was that many incidents that were reported with ASRS were from recreational use of a UAS.

Table 5

ASRS Flight Plan Data Summary

Instrument Form Categories	Number of Reports
Flight Plan	
IFR	37
VFR	8
None	38
N/A	25

Next, it was found that the majority of UAS incidents and accidents had been reported during the cruise phase of flight. Summary of the flight phase is provided in Table 6. Climb, descent and approach were identified in eight, seven, and five reports respectively. One report had no flight phase information.

Table 6

ASRS Flight phase data summary

Instrument Form Categories	Number of Reports
Flight Phase	
Climb	8
Cruise	77
Landing	2
Approach	5
Take-off	2
Descent	7
None	1
Other	3

After the analysis of the flight phase, data analysis of Airspace Classes showed that the majority of incidents and accidents had occurred in Class A and

Class G Airspace. Class E Airspace was identified in 20 reports. Summary of Airspace Class is shown in Table 7. Class D was identified in 11 reports, and 12 reports did not have information regarding Airspace Class in which the incident or the accident had occurred.

Table 7

ASRS Airspace Class Data Summary

Instrument Form Categories	Number of Reports
Airspace Class	
Class A	27
Class B	7
Class C	4
Class D	11
Class E	20
Class G	26
Special Use Airspace	1
N/A	12

From the analysis of contributing factors from the instrument forms, it was found that human factors were the major contributing factor for the cause of UAS incidents and accidents. Summary of contributing factor data is provided in Table 8. Other contributing factors that were most frequently identified in the reports were aircraft problem, procedural error or deviation, weather-related issues, airspace violation, equipment problem, chart or publication information, company policy, and airports. Only one report was without information for contributing factors.

Table 8

ASRS Contributing Factors Data Summary

Instrument Form Categories		Number of Reports
Contributing Factors		
	Human Factors	63
	Aircraft	30
	Equipment	7
	Procedure	44
	Weather	13
	Airspace Violation	10
	Chart or Publication	6
	Company Policy	4
	Airport	2
	N/A	1

The event category was further classified into four sub-categories: anomaly, detector, when detected, and result of the event. From the analysis, it was found that airspace violation and procedural deviation were identified in 40 reports. Summary of anomalies is provided in Table 9. ATC issue was identified in 15 reports. Excursion from assigned altitude was identified in 11 reports. An airborne conflict was identified in 10 reports. Clearance problems and equipment problems were identified in nine reports and loss of control of UAS was identified in seven reports.

Table 9

ASRS Event – Anomaly Data Summary

Instrument Form Categories	Number of Reports
Event (Anomaly)	
Procedure Deviation	40
Loss of Control of A/C	7
Airspace Violation	40
Clearance Issue	9
Equipment Problem	9
Excursion from Assigned Altitude	11
ATC Issue	15
Airborne Conflict	10

From the instrument forms, it was found that the majority of reported incidents and accidents were detected by the flight crew that was directly involved with the flying of the UAS. Summary of detector data from the reports is provided in Table 10. ATC detected the incident in 27 reports. The observer was identified as a detector in eight reports. Other people or a third party detected the event in seven of the reports. Ground personnel detected the incident in six reports. Two reports identified automation as the detector while four reports were without information on who detected the incident.

Table 10

ASRS Events – Detector Data Summary

Instrument Form Categories	Number of Reports
Event (Detector)	
Flight Crew	55
ATC	27
Ground Personnel	6
Observer	8
Automation	2
Other Person	7
N/A	4

Next, it was also found that the majority of the incidents and accidents were detected in-flight. Table 11 provides a summary of when the incident was detected.

Table 11

ASRS Events – When Detected Data Summary

Instrument Form Categories	Number of Reports
Event (When detected)	
In-flight	71
ATC	1
Routine Inspection	10
Service	1
Pre-flight	3
Other	8
N/A	12

A routine inspection was identified in 10 reports. Pre-flight was identified in three reports. Service and ATC were identified in one report. There were 12 reports without information regarding when the incident was detected.

After the incident or accident was detected, after the analysis, it was found that no action had been taken for the majority of the incidents. Summary of the results from the event of the incident is provided in Table 12. There were 19 reports that suggested that UAS was re-oriented after the event was detected. New clearance was issued in 14 reports. Evasive action was taken in 11 reports. Nine reports identified new advisory that issues to the flight crew as the result of the incident. In six reports, ATC assisted the flight crew.

Table 12

ASRS Events – Results Data Summary

Instrument Form Categories	Number of Reports
Event (Result)	
None Reported Action Taken	37
Took Evasive Action	11
Advisory Issued	9
New Clearance Issued	14
Re-oriented UAS	19
Exited Penetrated Airspace	4
Flight Canceled	2
A/C Damaged	6
ATC Assistance	6
Regained Control of UAS	5
N/A	7

Six reports identified that the aircraft was damaged as the result of the incident. Five reports identified that the flight crew regained control of their UAS while four reports identified that the flight crew exited the penetrated airspace. Two reports identified that the flight was canceled. Seven reports were without information regarding the result of the incident.

After the analysis, it was found that unsafe acts were the most frequently occurring HFACS category that was responsible for the cause of the reported incident or accident. Out of all the reports, there were a total of four reports without information regarding an HFACS category. Once the most frequently occurring HFACS category was identified, the next step was to identify the most frequently occurring HFACS sub-category. During the analysis, it was found that SBE and EV had significant involvement in the UAS incidents and accidents. Table 2 displays a summary of the ASRS data analysis. ASRS is an FAA voluntary, confidential reporting system. From the analysis, it was found that the majority of reports were filed by pilots who were flying their UAS for recreational purposes. However, some were being flown under stringent military regulations. From the analysis of the HFACS category for the most frequently occurring contributing factors, the category of the unsafe act was identified for the nature of the reported incident or accident while the organizational influence had only been identified four times.

Summary

The results of this study suggest that from the NTSB data analysis, the organizational influence was the most frequently occurring HFACS category for the contributing factor and probable cause(s) for UAS incidents and accidents while OP was identified as the most frequently occurring sub-category under the organizational influence. The ASRS data analysis suggested that unsafe act was the most frequently recurring HFACS category for the contributing factor and probable cause(s) for UAS incidents and accidents while SBE and EV were identified as the most frequently occurring sub-category under unsafe acts.

Chapter 5

Discussion

Research Summary

As the use of UAS is increasing across all industry sectors, chances of mishaps have also increased. During the last few years, there have been several incidents as well as accidents that involved a UAS either flying close to manned aircraft or UAS flying in unauthorized airspace. Although not all mishaps have been catastrophic, these incidents should not be taken lightly. Keeping in mind the Swiss Cheese Model, it can be said that these incidents and accidents occurred due to the lack of adequate defenses that could have mitigated risks associated with operating UAS in the NAS and near airports.

The primary purpose of the current study was to identify the HFACS category of the most frequently occurring contributing factors and probable cause(s) for UAS incidents and accidents using qualitative content analysis. For data collection, UAS incident and accident reports were obtained from the ASRS and NTSB databases, screened for UAS incidents or accidents, and analyzed to identify the HFACS category.

After the data analysis was completed and the HFACS categories were identified for the NTSB and ASRS reports, threats and consequences were identified from the reports. The next step was to visually represent the identified threats and consequences in a bow-tie diagram using Bow-TieXP software. The bow-tie diagram for the NTSB and ASRS results are discussed in this chapter.

Discussion

NTSB results. During the data collection, it was found that not all reports obtained had useful information regarding UAS incidents or accidents. All such reports were discarded, and only reports with information regarding UAS incidents and accidents were used for the data analysis. From the data analysis, it was found that the organizational factor was the most frequently occurring HFACS category identified from the NTSB reports analyzed. Within the organizational factor, OP was identified as the most frequently occurring sub-category of organizational influence. The identified HFACS category is appropriate for the NTSB reports that a majority of the reported incidents and accidents were from federal agencies or defense contractors. The NTSB reports were divided into several sections that identified every aspect of the reported incident or accident. These included findings, history of flight, damage to aircraft, personnel information, meteorological information, and aircraft information. Out of all these sections, findings were useful in terms of identifying contributing factors and probable cause(s) as it provided a summary of aircraft issues, personnel issues, and organizational issues that were associated in the reported incident or accident. However, not every report had complete information in the findings section. Therefore, the narrative section of the reports was also analyzed.

Although UAS operations for federal agencies are carried out under adherence to regulation, it was found during the data analysis that organizational influences played a significant role in the reported UAS incident or accident. These contributing factors consisted of pilot training, inadequate risk management process, task scheduling, its associated workload, pilot's incomplete knowledge of regulation and safe operating practices, and crew resource management (CRM) techniques. To make the bow-tie diagram concise, all reports that had been identified under OP were further analyzed. Reports that had a similar chain of events were visually represented in one bow-tie diagram resulting in a total number of four bowtie diagrams. In total, two hazards were identified: UAS flying and UAS landing. For UAS landing, hard landing or abnormal runway contact and an aerodynamic stall/spin were identified as the top events. For UAS flying, total engine failure and mid-air collision were identified as the top events.

Hard Landing or Abnormal Runway Contact. The bow-tie diagram for a hard landing or an abnormal runway contact is shown in Figure 6. The left-hand side of the bow-tie diagram shows all the identified threats associated with a hard landing or abnormal runway contact and the barriers that could be placed as defenses to mitigate the risk associated with the identified threats. If the top event occurs, the right-hand side shows all the consequences that could result from the top event and the barriers that could be placed to control the risks associated with each consequence. For the top event in Figure 8, distraction, tailwind, delayed action, visual illusion, UAS disorientation, and loss of control (LOC) of UAS were identified as the major threats that could lead to a hard landing or abnormal runway contact. Next, each threat's contribution to the top event was also identified.

Distraction, delayed action, visual illusion, and UAS disorientation were identified as the major contributors to the top event. A LOC of aircraft and tailwind were identified as the medium contributors to the top event. It was clear that in order to mitigate the risk associated with these threats, specific barriers were necessary to implement in UAS operation in order to make sure that events such as hard landing are avoided. These barriers were training, flying under supervision, flying in line of sight (LOS), avoiding first-person view (FPV) flying, flight planning, and procedural knowledge, and compliance.

On the right-hand side of the top event, all the consequences that could arise from the top event were identified. These consequences included damage to the nose wheel, damage to nearby property, and damage to UAS. Out of all the consequences, UAS damage was categorized as a major concern while damage to a nose wheel and property was categorized as medium concerns. The barriers on the right-hand side were identified in such a manner that if the top event occurs, the scenario does not escalate into a consequence. Barriers such as weather evaluation, procedural knowledge, and compliance, not flying near a property, and adequate supervision can be implemented to ensure that a top event does not escalate into an undesired consequence.

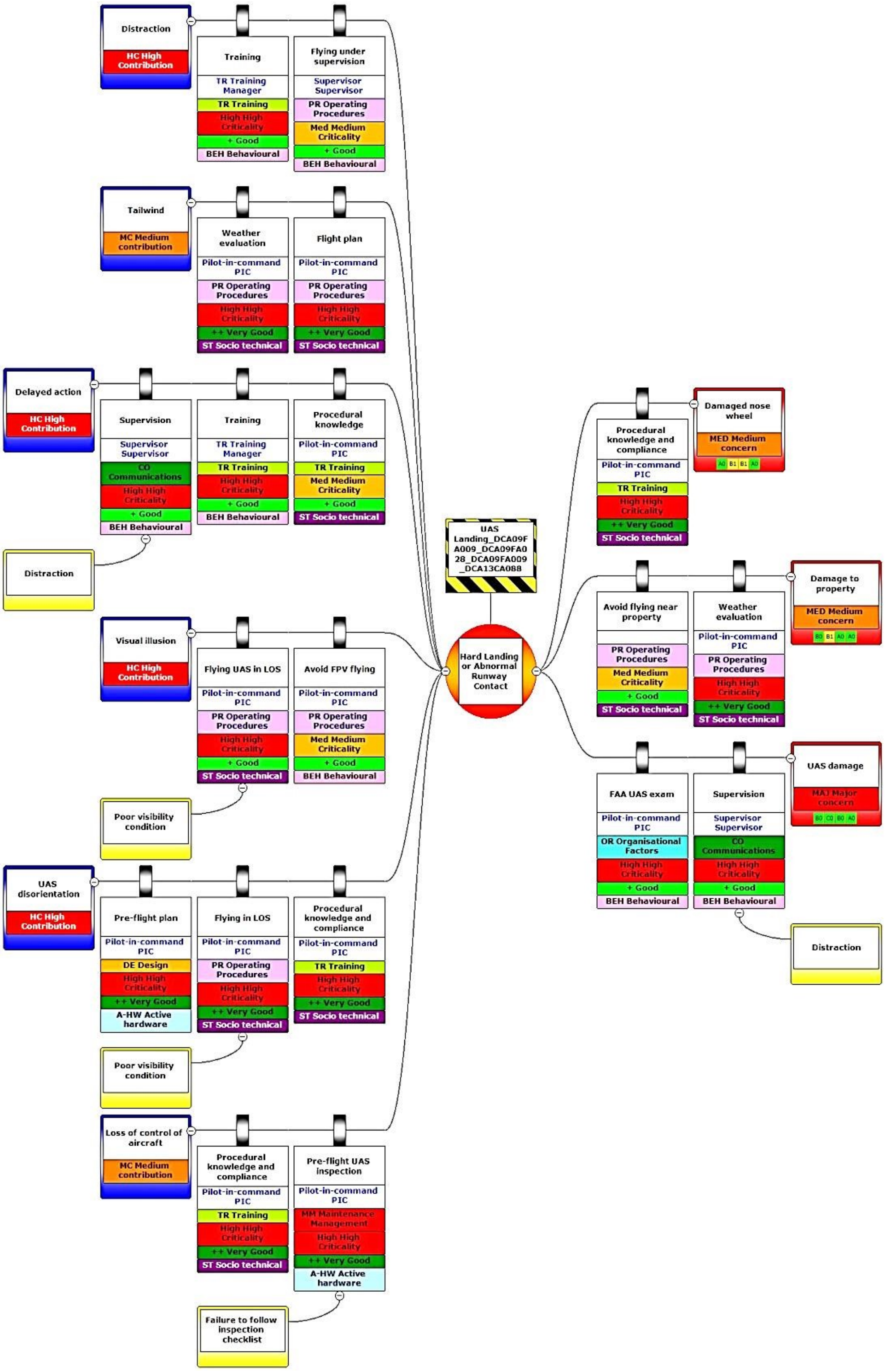

Figure 6: Bow-tie Diagram For Hard Landing And Abnormal Runway Contact

Additionally, the Bow-TieXP software provides the capability to include details regarding barriers consisting of personnel responsible, basic risk factor (brf) code, the criticality of the barrier, effectiveness of the barrier, and barrier type. Personnel accountable helps identify who is responsible for the identified barrier's current and future state. The brf code indicates the code the barrier belongs to such as hardware, design, maintenance management, operating procedures, error-enforcing conditions, incompatible goals, organizational factors, communications, training, and defenses. The criticality of the barriers helps identify how critical the barrier is for the threat. The effectiveness of the barrier helps identify how effective the barrier will be once it is implemented. Barrier type helps identify the function of a barrier. In addition to identifying the function of the barrier, it also helps to identify different types of systems that be used to implement the function of the barrier. The systems available in the software are behavioral, active hardware, socio-technical, continuous hardware, and passive hardware. This helped in identifying the level of detail in barriers such as whether the barriers were present or absent and any other relevant aspect necessary in understanding the role of barriers in mitigating risk corresponding to threats. From the bow-tie diagram and the reports, it was concluded that even though the majority of barriers were present, they were not adequately implemented to mitigate the risk. Also, from the bow-tie diagram, it was identified that distraction was the primary escalation factor for the barriers. An escalation factor, in a bow-tie diagram, helps identify the weakness that may be present in a barrier.

Aerodynamic Stall/Spin. Aerodynamic stall/spin event was visually represented next in the bow-tie diagram. The chances of an aerodynamic stall or spin are rare in nature unless the pilot-in-command (PIC) decides to perform high-speed maneuvers or tries to fly their UAS beyond its performing capabilities without any necessary training. In such a scenario, chances of an aerodynamic stall or spin drastically increases. Figure 7 shows the bow-tie diagram for the identified top event. The identified threats included delayed action and the loss of a communication link. Wherein, delayed action was categorized as a high contributor to top event while the loss of a communication link was categorized as a low contributor to the top event.

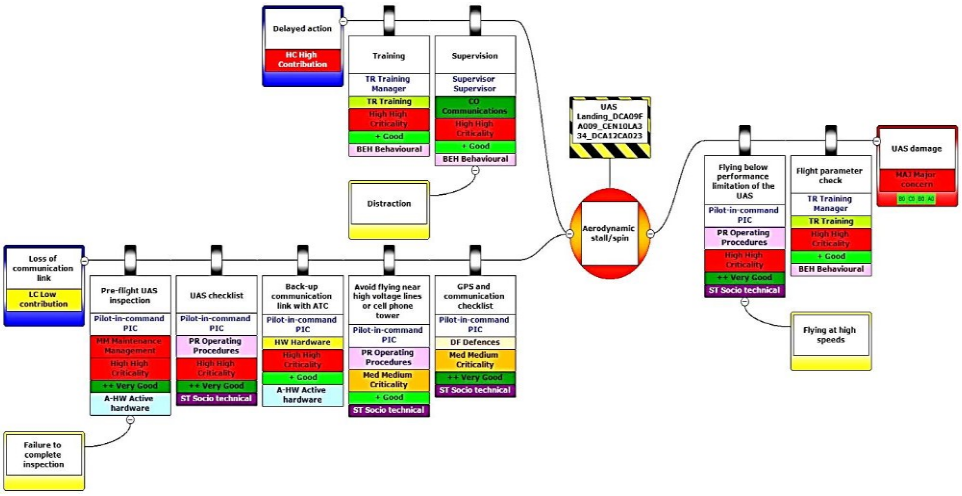

Figure 7: Bow-tie Diagram for Aerodynamic Stall/Spin

Training and supervision were identified as barriers that could be placed to ensure that any risk associated with delayed action is mitigated. Both training and supervision play a crucial role in reducing the risk of UAS going in an aerodynamic stall of spin as the PIC can be trained depending upon the UAS model, not to perform maneuvers beyond their UAS performance capabilities.

Also, after the PIC has received their training, they can be allowed to fly their UAS under strict supervision to ensure that they fly under the performance capabilities of the UAS. Distraction was identified as an escalation factor for supervision. There can be occasions where the supervisor is distracted due to a myriad of reasons and fails to notice that the PIC is not flying within the UAS performance limits. This could result in an aerodynamic stall even under supervision. Therefore, the supervisor should make sure that he or she is free from distractions during the flight.

Pre-flight inspection, UAS checklist, not flying near high voltage lines or cell phone towers and, GPS and communication checklists were identified as barriers that could be placed to ensure that risks associated with loss of communication link can be mitigated. Pre-flight inspection is a crucial part of a flight and ensures that all the flight components are in perfect working condition. The pre-flight inspection includes checking the battery level on the UAS and controller, making sure the controller is connected to the UAS, components such as the rotor or camera are firmly attached to the main body, and that the device the PIC uses to monitor the UAS is fully charged and connected to the UAS. The UAS checklist is a step-by-step checklist that allows the PIC to check for each component of their flight. Having a flight plan can help the PIC identify if anything is missing or incomplete. Flying near high voltage lines or cell phone towers can interfere with the communication link between the controller and UAS which could result in a lack of the initial communication set-up with the UAS. Therefore, it is not advisable to fly near high voltage lines until the necessary precautions are taken. GPS and communication checklists may fall under a UAS checklist and are generally used to ensure that the controller and UAS have adequate GPS connection before the flight is initiated. One escalation factor identified for pre-flight inspection was the failure to complete an inspection or perform an incomplete inspection. This means that the PIC does not make sure that adequate communication is set-up before the flight that could result in a loss of a communication link between the controller and the UAS.

One of the primary consequences associated with an aerodynamic stall or spin is UAS damage which was categorized as a major concern. Whenever an aerial system is forced to perform beyond its performance capabilities, it can result in a damaged airframe. For small and lightweight UAS, damage can be pervasive depending upon the maneuver it was performing or the speed that it was flying at the time of the aerodynamic stall or spin. The barriers that can be placed to ensure that the top event does not escalate to consequences are flying below the performance limitation of the UAS and checking flight parameters such as speed and altitude. These barriers, if properly implemented, can play a crucial role in preventing an aerodynamic stall or a spin. However, recreational flyers tend to be more “adventurous” when flying their UAS. If a recreational flyer does not have much experience in flying, they might want to fly at higher speeds and altitude to test their UAS’ capabilities resulting in a scenario where an aerodynamic stall or spin is inevitable.

Total Engine Failure. Next, total engine failure was visually represented using the bow-tie diagram. Although the chance of an engine failure is rare, it is still a viable top event that can increase the level of risk associated with flying a UAS. A bow-tie diagram for total engine failure is shown in Figure 8. The threats that were identified that could lead to the top event are icing conditions, loss of voltage in batteries, foreign object damage (FOD), delayed action, engine overheating, and failure of engine components. Out of all of these threats, icing conditions, loss of voltage of batteries, and engine overheating were categorized as low contributors to the top event. FOD was identified as a medium contributor while delayed action and failure of engine component were identified as a major contributor to the event of an engine failure. For icing condition weather evaluations, pre-flight planning and post-inspection flight were identified as barriers that could mitigate the risks. Weather evaluation and pre-flight planning, especially, for colder weather conditions, can be helpful to the PIC in evaluating if the current weather condition is permissible for flying. Icing conditions for fixed wings UAS not only reduces the ability of wings to generate lift; it significantly increases drag generation that could adversely affect UAS performance. After the evaluation, if the PIC believes it is feasible to fly in icing conditions, the PIC must perform a thorough post-flight inspection to ensure that all control surfaces or engine components are free of ice. UAS checklist, pre-flight UAS inspection, and charging batteries to an optimum percentage were identified as barriers for loss of voltage from batteries. UAS checklists and pre-flight inspections are both important procedures before initiating a flight. These barriers can help the PIC in ensuring that the controller, as well as the UAS batteries, are charged to the optimum level. If these procedures are not followed, it results in flying the UAS with a low level of charge in the battery resulting in mid-flight loss of power to the engine and ultimately could result in UAS failure. To ensure this does not happen, the PIC should ensure that batteries are fully charged and spare batteries are available in case of a battery failure or loss of voltage occurs. FOD is dangerous to engines and the structure of the UAS. The PIC is responsible for ensuring that a thorough pre-flight inspection is completed to ensure that the launch area is clear of FOD. Delayed action is a threat that is ever present if the PIC is not aware of procedural knowledge. In the event of an engine failure, any delayed actions can lead to loss of control and failure of UAS.

The risks associated with a total engine failure can be mitigated by ensuring that the PIC has a good understanding of the procedure to undertake in case of an engine failure. Supervision is another barrier that could be used to ensure that an inexperienced PIC can handle engine failure properly. However, supervisors can be prone to distraction which was identified as an escalation factor for supervision.

Engine overheating although rare can occur if the PIC decides to fly their UAS beyond its performance limits. For example, if a UAS is flown at high speed for a prolonged time, it could overheat the engine components. If immediate actions are not taken, the engine overheating could lead to engine damage or engine failure. To mitigate risks, the PIC must know the performance limitations of their UAS and procedures in handling any situations that involve engine overheating. Inadequate performance evaluations were identified as an escalation factor for performance limitation evaluation. Failure of engine components can be catastrophic if the risk is not mitigated. One of the best ways to ensure that this does not happen is for the PIC to conduct a thorough pre-flight inspection to check for visible damage in the engine or abnormalities in engine components.

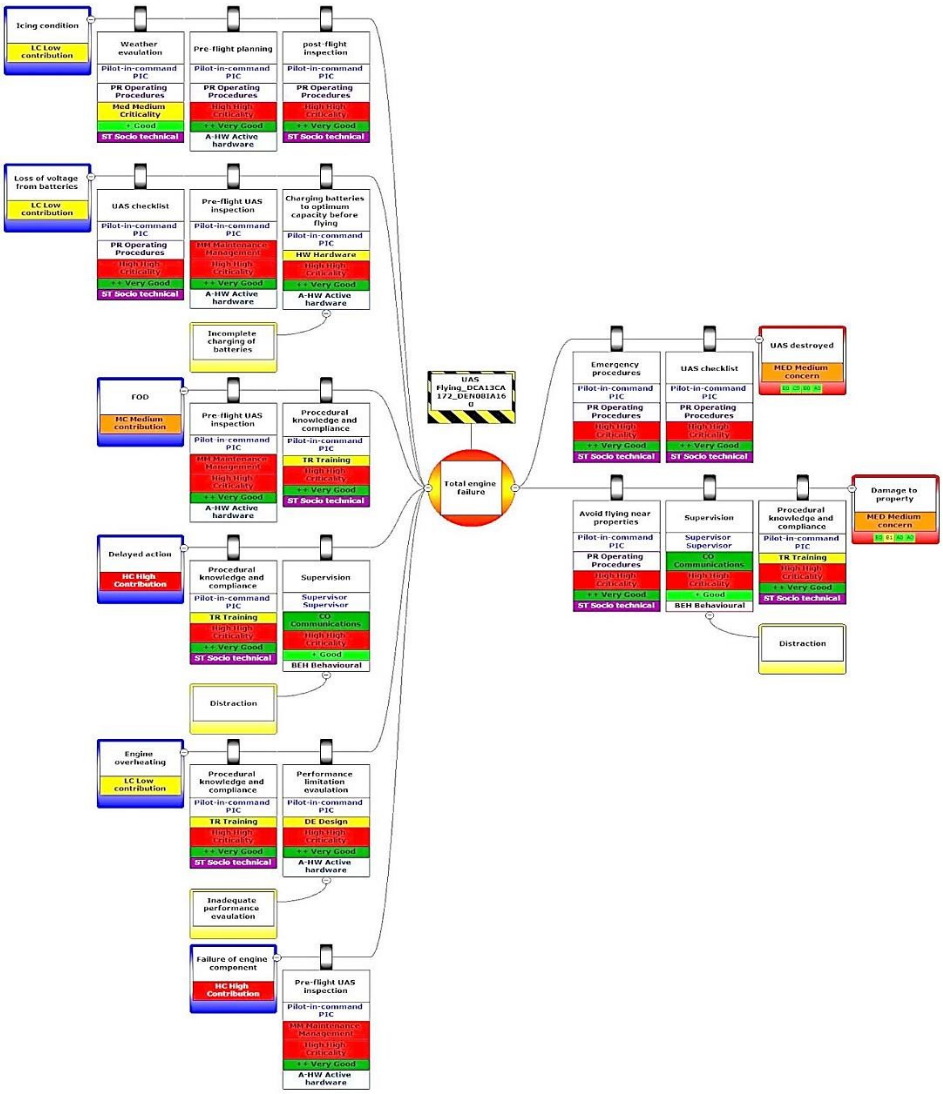

Figure 8: Bow-tie Diagram for Total Engine Failure

UASs can be destroyed if a total engine failure event is reached. Even if the top event occurs, barriers such as emergency procedures and protocols and UAS operating checklists can be used to ensure that the UAS is brought down safely. Emergency procedures are a vital step in identifying what has happened and what needs to be done if the top event has occurred. It is the sole responsibility of the PIC or the supervisor to ensure that an emergency procedure checklist is available in case of engine failure. Another consequence identified from the bow-tie diagram was damage to property. If the PIC flies near the property, damage to the property can occur if an engine failure occurs. To ensure that this consequence is not reached, barriers such as avoid flying near property, supervision, and procedural knowledge and compliance could be so the PIC can steer a UAS away from the property. This can only happen if the PIC understands the risks associated with flying near the property and has a good understanding of the procedures to follow if flying near the property. UAS getting destroying and damage to property were identified as medium concerns. However, distraction was identified as an escalation factor as it may result in slower response time in the event of an engine failure.

Mid-Air Collision. The final event identified from NTSB data analysis was a mid-air collision. Mid-air collisions are a severe consequence that could result in multiple fatalities if adequate safety measures are not taken to ensure safe operation of UASs and manned aircraft in the NAS and near airports. The bow-tie diagram for a mid-air collision is shown in Figure 9. Flying close to manned aircraft, flying UASs in unauthorized airspace, poor visibility, irresponsible flying, and flying beyond LOS were identified as threats that could lead to a mid-air collision between a UAS and a manned aircraft. Out of these, flying close to manned aircraft and irresponsible flying were identified as major contributors to the top event while poor visibility and flying beyond LOS were identified as medium contributors to the top event. A mid-air collision between a UAS and manned is rare, but there have been instances in the past where there was a mid-air collision in which the UAS was destroyed, and manned aircraft was able to land without a dire consequence. This does imply that all the safety measures are in place as the manned aircraft was able to land without any fatalities. If not mid-air collision, then flying close to a manned aircraft can lead to a mid-air collision if the risks associated with it are not mitigated. Barriers such as NOTAMs, airspace awareness training, geo-fencing, and UAS traffic management can be placed to ensure that a UAS does not come near a manned aircraft. NOTAMs, inform ATC wherein the PIC of the UAS can provide details regarding the nature of their flight operations. ATC can then inform manned aircraft that may have their flight or approach path near the UAS operation. NOTAMs is an efficient way of informing concerned parties about UAS operations which can significantly reduce the risks of operating UASs near manned aircraft. One escalation factor identified for NOTAM was that the PIC might not know how to issue a NOTAM which could increase the risks of operating UASs near an airport.

During data analysis, it was also found that many pilots had some or very little understanding of airspace classification. This resulted in a PIC flying where they were not allowed or where authorization was not given from ATC. Airspace awareness training needs to be implemented to ensure that the PIC is aware of the surrounding airspace and what needs to be done to ensure safe operations, mainly, in airspace that requires ATC authorization.

UAS traffic management is maintaining a smooth flow of UASs within the NAS and near airports. This can be generally achieved by ensuring that a PIC request authorization from ATC to operate their UAS. For this particular barrier, ATC plays an integral role in keeping a safe distance with manned aircraft and the UAS. Poor visibility conditions can result in a perceptual error where the PIC may not be able to accurately locate a UAS' position or have a clear field of vision, both of which could result in a mid-air collision. Weather evaluation and pre-flight planning were the barriers identified to reduce the risk associated with poor visibility. It is always a good measure to perform a weather evaluation and pre-flight planning before a flight as it helps evaluate whether the conditions are good enough for LOS flying.

Flying beyond LOS can be potentially dangerous as the PIC may not be entirely sure about the UAS' position. Flying beyond LOS could also result in a delayed action and slow response time. To encounter these threats, procedural knowledge is a must for the PIC. If the PIC plans to fly beyond LOS, then it is the PIC's responsibility to have a good understanding of the procedural knowledge and have a checklist with them to ensure that aspects of the mission are followed. If the PIC wants to fly beyond LOS, it is always helpful to keep a visual observer during the operation. Under procedural knowledge, the PIC should have a good understanding of the UAS being flown and regulations that govern flying beyond LOS.

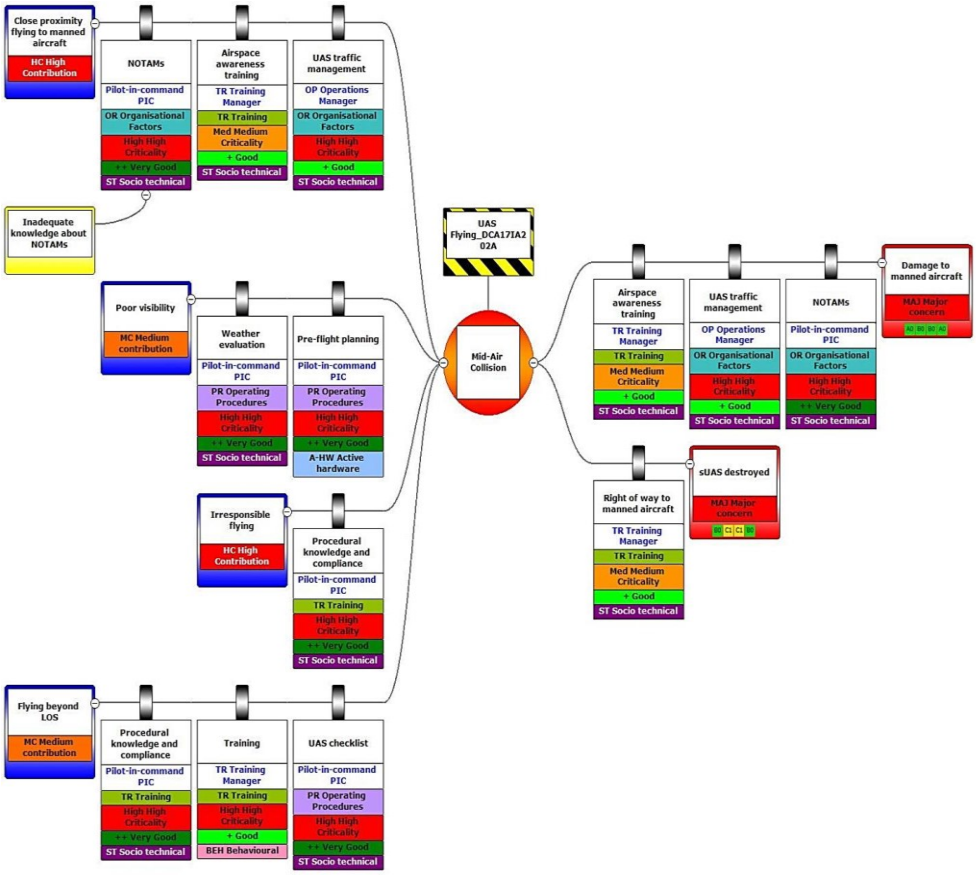

Figure 9: Bow-tie Diagram For a Mid-Air Collision

Two significant consequences that could arise from a mid-air collision between a manned aircraft and a UAS are damage to manned aircraft and a UAS being destroyed. Both of these consequences are a major concern. To ensure that damage to manned aircraft does not occur, airspace awareness training, NOTAMs, and UAS traffic management should be placed to ensure that damage to manned aircraft does not take place. Mainly, UAS traffic management is an essential barrier that can ensure that manned aircraft always have the right of way when UAS is flying nearby. NOTAM is another barrier that will give essential information to the pilots of manned aircraft about UAS' activity in their proximity. Although pilots of manned aircraft have an excellent understanding of airspace classification, UAS pilots may be unaware of the classification and might fly in airspace without authorization. If there is a mid-air collision between a manned flight and a UAS, a UAS may decimate due to the impact forces. In order to prevent this consequence from happening, it is the PIC's responsibility always to give the right of way to manned aircraft. By doing so, risks of a mid-air collision can be drastically reduced.

ASRS Results. The ASRS reports as previously mentioned are submitted voluntarily. Therefore, a majority of reports that have been filed were from a PIC or a visual observer. After the data analysis, it was evident that unsafe acts were the most frequently occurring HFACS category while exceptional violation was the most frequently occurring sub-category under unsafe acts. Keeping in mind the format and the nature of the information that was available in the reports, unsafe acts seemed to be an appropriate result for the ASRS reports. One drawback of ASRS reporting is that not everyone is accustomed to the online reporting system. Despite numerous incidents or accidents being reported, there may be more incidents unreported by the PIC, visual observer, or the third party who notices the unusual UAS activity due to a lack of awareness of the ASRS reporting system. Without knowing the risks that are associated with unreported incidents, a more thorough risk assessment cannot be accomplished.

For the current study, all reports that had unsafe acts were analyzed. From this, it was found that the majority of reports had reported airspace violations in the form of flying within five miles of an airport, excursion from assigned altitude, and operating UAS without authorization from the FAA and the ATC. Also, other top events identified were equipment problem, unauthorized operation of a UAS near a moving train, UAS operating over a group of people, UAS operator forgetting to inform ATC regarding their operation, and UAS flying close to a building. For the bow-tie diagram, keeping in mind the top events identified from the reports, a single bow-tie group of UAS flying was created. Under this group, all identified top events were divided into UAS flying within five miles of an airport, operating near an automotive or aircraft or operating over people, and flying near a building. The bow-tie diagram for these three top events is discussed in this section.

Flying Within five Miles of an Airport. The first identified top event was a UAS flying within five miles of an airport. From the reports, it was evident that the UAS operator was unaware of the regulation that they are not supposed to operate a UAS within five miles of an airport. The majority of these reports were from recreational UAS flyers. Although these incidents did not result in a severe consequence, there are risks associated that must be mitigated to prevent future undesired consequences. From the reports, it was also identified that the PIC did not realize that UAS operators are not permitted to fly within five miles of an airport. It is this deficiency in the risk management that poses the most significant risk for UAS operating near or at airports. The other threats and the consequences that could arise from operating UAS within five miles of an airport are shown in Figure 10.

The threats identified include a near mid-air collision (NMAC), poor visibility, flying out of LOS, delayed action, loss of communication link, and UAS disorientation. NMAC, flying out of LOS, delayed action and UAS disorientation were identified as major contributors to the top event while poor visibility conditions and loss of communication link were identified as low contributors to the top event. One of the most imminent threats of flying a UAS within five miles of an airport is an NMAC. Flying a UAS five miles within an airport brings the UAS right in the approach path of a manned aircraft which increases the risk of an NMAC. The reports, as shown before, showed that the majority of UAS operators did not realize that UASs were not permitted to fly within five miles of an airport, and also did not realize that their UAS was within five miles of an airport. These reports pointed out the UAS operator's lack of knowledge regarding rules and regulations.

In order to mitigate the risks associated with NMAC, the barriers identified were flight plan and procedural knowledge compliance. It is advised that UAS operators develop a proper flight plan before commencing their flight. The flight plan would help identify the airspace for the UAS flight and how close the airspace is to an airport. A flight plan will show the procedures to follow. Implementing these barriers would significantly reduce the risk of an NMAC

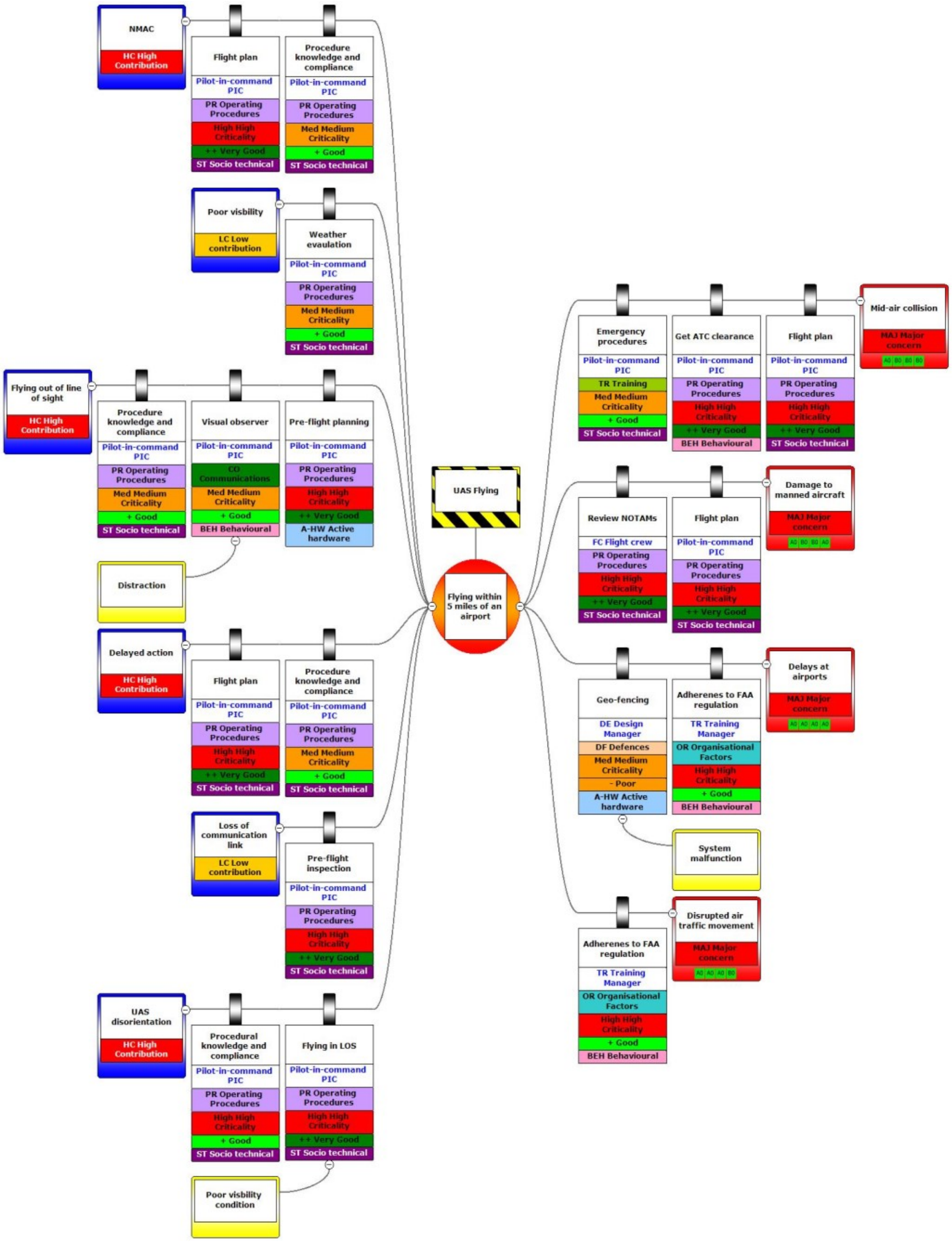

Figure 10: Bow-tie Diagram for Flying a UAS Within Five Miles of an Airport

. Poor visibility can also be a threat that leads to a PIC flying within five miles of an airport due to a lack of visibility that a UAS was too close to an airport. In order to mitigate risks associated with a reduced visibility condition, the PIC must conduct a complete weather evaluation and include it in the flight plan.

Flying out of LOS is another threat that poses risks. A few reports mentioned that a PIC after flying a UAS beyond LOS realized that the UAS was dangerously close to an airport. Therefore, a PIC must always operate the UAS within the LOS. This occurs when the PIC has a good understanding of procedural knowledge and regulations, has a visual observer, and completes a pre-flight briefing about the nature of the operation. From all the barriers, distraction was identified as an escalation factor for the visual observer. Next, delayed action when flying a UAS can result in the UAS coming in contact with a manned aircraft or airport perimeter. Both of these are considered a dangerous activity that can potentially shut down an airport or result in a mid-air collision. The risks associated with delayed action can be mitigated by implementing a flight plan and making sure that the PIC has a good command of procedural knowledge. Having a flight plan will help in knowing where a PIC plans to carry out their mission. By knowing beforehand where they are going to fly their UAS or their mission, chances of delayed action are brought down significantly. The risks associated with loss of communication link can be mitigated by conducting a pre-flight inspection to make sure that the UAS is connected to the controller and vice-versa. It is also helpful to ensure that UASs and controllers are charged to an optimum level for the mission. One major issue that could arise for new UAS operators is UAS orientation mid-flight. Due to the small structure and design of a UAS, sometimes, it can be difficult for new flyers to identify the orientation or the direction their UAS is flying. Barriers such as flying in LOS and procedural knowledge can help a PIC understand the UAS orientation. It is essential to fly in LOS if the PIC is unsure of the orientation of the UAS. The PIC could determine its orientation and take necessary action to bring the UAS back if it had deviated from the intended flight path. However, poor visibility is a concern for flying in LOS because if the visibility is deteriorating and the PIC is unaware of the UAS orientation, it is advisable to abort the flight and wait for visibility to improve.

For the current top event, there were four consequences identified: Mid-air collision, damaged to manned aircraft, delay at airports, and disruption of air traffic movement. Each of these was categorized as a major concern to the top event. One of the most recognizable consequences of flying a UAS within five miles of an airport is a mid-air collision with a manned aircraft. Flying close to an airport is not only a breach of federal regulation to operate a UAS; it drastically increases the level of risk for both manned aircraft and the UAS. Emergency procedures and flight plans are the barriers that can be used to ensure that the consequence as mentioned earlier is not reached. If the PIC plans to fly a UAS within five miles, it is necessary that ATC authorizes the operation before the flight. Over the past few years, there have been several instances where a UAS was sighted close to an airport. However, one issue with implementing this barrier is that not everyone is aware of or knows how to contact ATC for authorization and does not know what to do next after authorization is received. In one of the ASRS reports, the PIC had obtained the authorization from ATC, but when the flight was initiated, the PIC forgot to call ATC again to inform them about his flight. It was only after the flight was completed, the PIC realized that even after receiving authorization, he still needed to inform ATC before the flight. It is necessary that the PIC knows what procedures to follow to fly a UAS within five miles of an airport. In addition to the previously described consequence, damage to manned aircraft can also be considered a consequence that the PIC would want to avoid. It must be understood that the manned aircraft are bigger and more potent than UASs and an impact between them will destroy the UAS. This impact can also severely damage manned aircraft. Several incidents of damages caused by UASs to manned aircraft were previously discussed in Chapter 1. To make sure that this consequence is not reached, barriers such as a review of NOTAMs by the flight crew of manned aircraft and flight plan by the PIC of the UAS can be implemented to ensure that both parties are aware of the presence of other aircraft. This way, the UAS can be at a safe distance from any manned aircraft and any chance of potential damage to manned aircraft is significantly reduced. Recently, UAS sightings have become an issue at airports. The immediate action taken by airport authorities is to ground all flights. This causes a domino effect and affects the entire day's operation at an airport resulting in multiple delays and disrupts traffic movement at the airport and surrounding airports. Barriers such as geo-fencing and adherence to FAA regulations can be implemented to ensure that this does not happen. Having a general awareness of FAA regulations will help the PIC understand the associated risks and what can be done so that risks are not escalated to a level where an undesirable consequence is reached.

Flying a UAS Near an Automotive, an Aircraft, or Over People. The second top event identified was operating a UAS near a moving automotive or an aircraft and over a group of people. For the top event, poor visibility, loss of communication link, delayed action, flying out of LOS, and UAS disorientation was identified as threats that pose a risk when operating UAS near a moving automotive or over people. Out of all the threats mentioned above, poor visibility and loss of communication link were identified as low contributors to the occurrence of the top event. Whereas, UAS disorientation, delayed action, and flying out of LOS were identified as a high contributor of risk associated with operating UASs near an automotive and over people. The bow-tie diagram for the aforementioned top event is shown in Figure 11. Any risks associated with poor visibility, as mentioned in previous sections, can be mitigated by making sure that the PIC completes a thorough weather evaluation before the flight.

Loss of communication of link is another threat that poses a high level of risk particularly for operating UAS over people. In the case of a lost communication link, the UAS may go rogue and injure individuals directly in the path of the UAS. Barriers such as pre-flight inspection, UAS checklists, communication checklists, and GPS checklists can be implemented to ensure that all critical communication links are set before a flight.

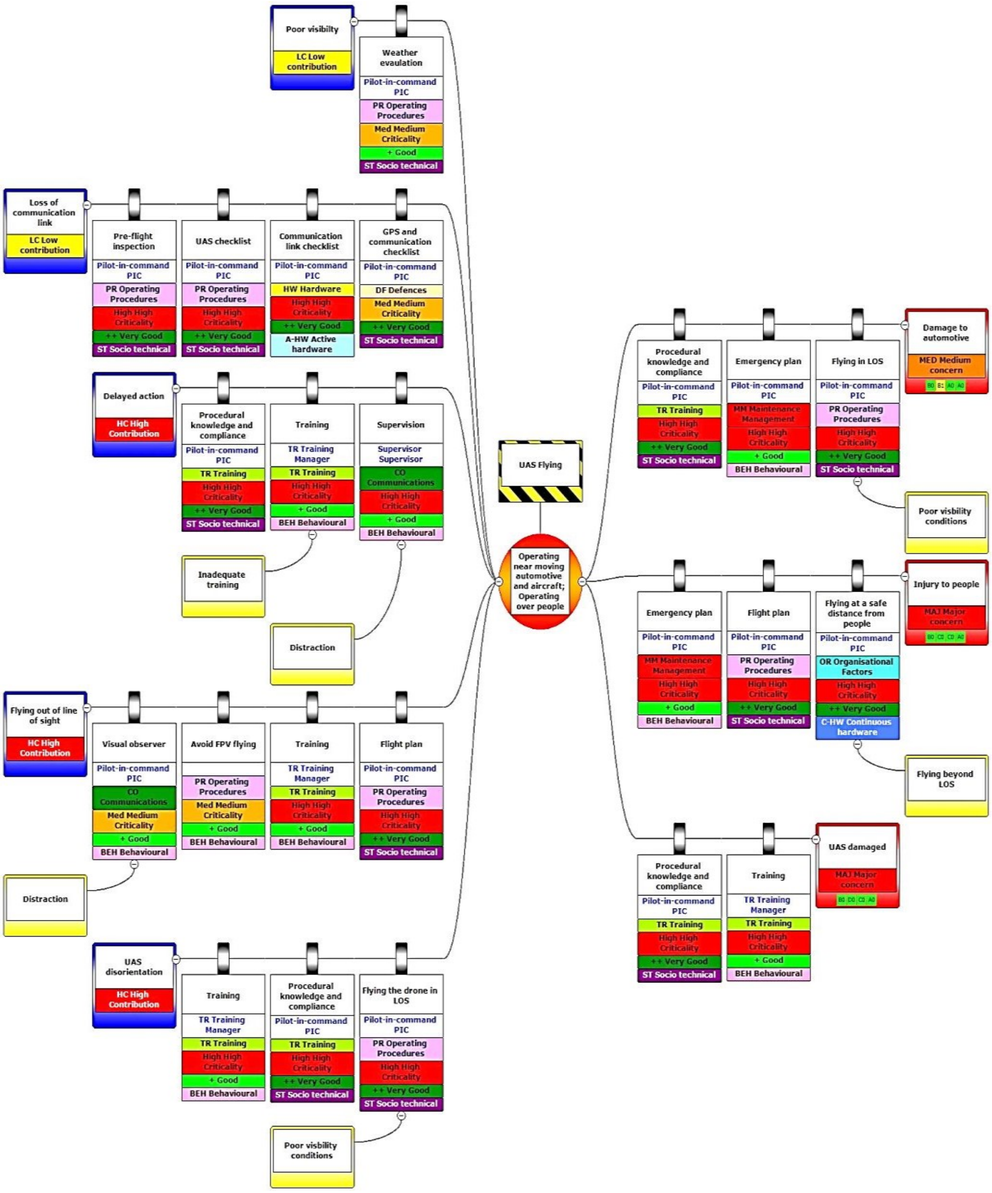

Figure 11: Bow-tie Diagram for Flying a UAS Near an Automotive, An Aircraft or People

It is to be noted that it is the sole responsibility of the PIC to make sure that adequate communication link is established between the controller and the UAS. Delayed action is another threat that poses a significant threat to the occurrence of the top event. A delayed action can result in a collision with the automotive or UAS falling on people. Barriers such as flying under supervision, having a good command of procedural knowledge and compliance as well as training can mitigate risks associated with operating a UAS over people. Even though flying over people is not permissible, it is advised that the PIC makes adequate emergency plans to avoid people getting injured due to a UAS failure. However, as previously mentioned, distraction was identified as an escalation factor that could limit the effect of training as well as a supervision barrier in risk mitigation. Risks of hitting a moving automotive or injuring a person significantly increase if the PIC is flying beyond LOS. Barriers such as having a visual observer, avoiding flying in FPV, providing training, and having a flight plan can mitigate the risk. Even if the PIC wants to fly beyond LOS, it is their responsibility to ensure that a visual observer is present who can maintain visual contact with the UAS at all times. As mentioned in the previous section, UAS disorientation can prove to be very dangerous especially when it is being operated near a moving automotive or over a group of people. UAS disorientation occurs when the PIC is not aware of the direction the UAS is flying. If the PIC is unaware of the UAS' direction, it can hit a moving automotive and sustain damage as well as cause injuries to people in it. Barriers such as training, procedural knowledge and flying a UAS in LOS can be implemented to ensure that the PIC knows the orientation of the UAS they are operating. Training can especially help a PIC understand how UASs operate mid-air which can help them identify UAS' position concerning themselves. When a UAS is operated beyond LOS, the risk of losing the UAS orientation greatly increases. Therefore, it is advised that the PIC must always operate their UAS in LOS so visual confirmation about the UAS' orientation can occur.

For the top event, damage to automotive, injury to people, and damage to UAS were identified as a consequence that could arise from flying a UAS close to a moving automotive or over people. All three consequences were identified as major concerns. If a UAS is flying near a moving automotive, the first consequence that could arise is a UAS hitting the automotive and damaging it. This could also result in a UAS getting damaged or destroyed. Barriers such as having an emergency plan as part of the checklist, procedural knowledge, and compliance and flying in LOS, can mitigate the risk if the top event is reached and limit the severity of the effects of consequence. These barriers can help the PIC understand what the risks involved are if they are going to operate their UAS near a moving automotive. Another consequence that could arise is an injury to people. If the top event is reached, then barriers such as an emergency plan, flying at a safe distance from people, and flight plan can be implemented to ensure that there are no injuries if the UAS is to be operated near or around people.

Flying Near a Building. Flying near a building was the third top event that was identified from the data analysis. People often fly their UASs for recreational purposes too close to a building or a property for a variety of purposes. Flying near a building can be very dangerous if adequate steps are not taken to mitigate the risks associated with it. The bow-tie diagram for flying near a building is shown in Figure 12. From the bow-tie diagram, loss of communication link, delayed action, inexperienced pilot, UAS disorientation, LOC of UAS, and flying out of LOS was identified as threats that could lead to the occurrence of the top event. Out of these, loss of communication link was identified as a low contributor to the occurrence of the top event while delayed action, inexperienced pilot, UAS disorientation, LOC of UAS, and flying out of LOS were identified as high contributors to the occurrence of the top event.

Although LOC is rare, the risks associated with it cannot be ignored. Barriers such as a pre-flight checklist, procedural knowledge, and pre-flight planning can be implemented to mitigate the risks. Without a pre-flight checklist, the communication link that needs to be established between the controller and the UAS may not be adequately established resulting in a communication lag or loss during mid-flight. Having a pre-flight checklist assists the PIC to check all the necessary items, particularly, whether proper communication is established between the controller and the UAS. Procedural knowledge, in this case, refers to the PIC having a good understanding of how to set-up a communication link between the controller and the UAS. New pilots need to be trained with procedural knowledge in order to mitigate the risk of an incomplete checklist procedure. Delayed action is another threat that plays a significant role in an incident or an accident when flying near a building. Barriers such as supervision and training can be implemented to ensure that when the PIC is operating near a building, and the UAS gets dangerously close to a building, the PIC can make corrective decisions in the form of maneuvers to steer away from the building.

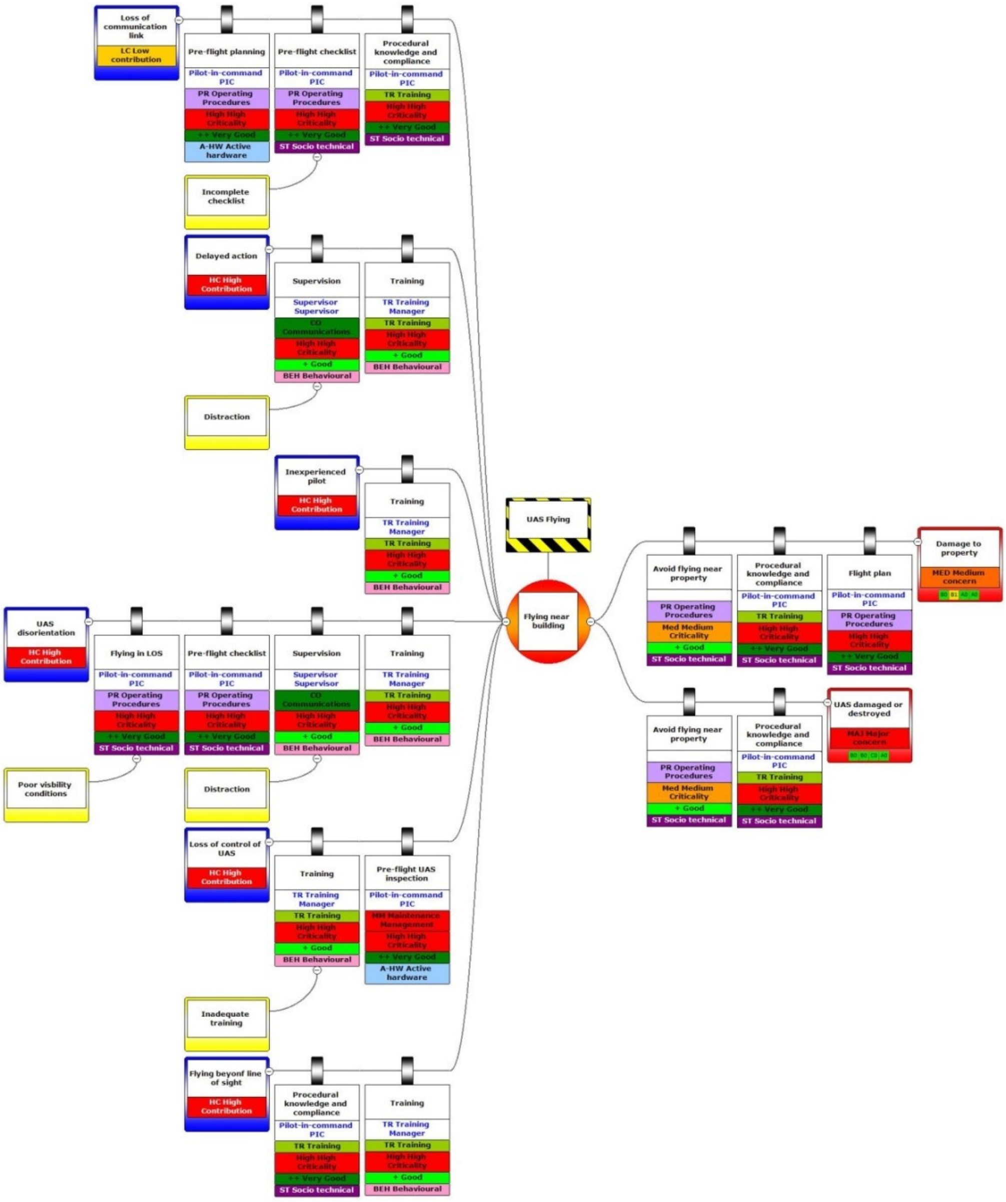

Figure 12: Bow-tie Diagram for Flying a UAS Near a building

If the PIC is untrained, it is advisable that a supervisor is present at all times to ensure that adequate actions are taken promptly. As previously mentioned, whenever a supervisor suggests a barrier, distraction can be an escalation factor. An untrained pilot or an inexperienced pilot is another threat that cannot be ignored. Not everyone who buys or flies a UAS is an experienced pilot. Everyone buys it for the first time, and they need time and practice to fly it efficiently. Inexperienced flying near a building can be dangerous especially when the PIC is unaccustomed to the user interface of the UAS. One barrier that can be implemented to mitigate risks associated with an inexperienced pilot is training. Training is a crucial part of flying a UAS as with different model of UAS, the controller is different and so is the user interface. Therefore, it is highly recommended that whenever a PIC is flying a UAS, the PIC needs to get familiar with the user interface of that particular UAS to mitigate risks, particularly, if flying near a building.

UAS disorientation is another threat that is in many ways inter-linked with an inexperienced pilot. UAS disorientation, if flying near a group of closely located buildings can result in fatal consequences. Risks of flying near a building significantly increase when an inexperienced pilot loses track of their UAS' orientation. To mitigate risks, barriers such as flying in LOS, supervision, and training can be implemented to ensure that the PIC always has a good idea of their UAS' orientation. It is best to fly with a third party that can act as a supervisor to provide details regarding the UAS orientation and directs the PIC to re-orient the UAS as necessary. It is advisable that when the PIC is flying with a group of people, the PIC should assign the task of being a visual observer to ensure that a UAS is staying on its intended flight path. If the PIC is flying solo, it is the PIC's responsibility to fly in the LOS to ensure the UAS is flying in its intended flight path. However, poor weather conditions can add difficulty in maintaining constant visual contact with the UAS. Under such circumstances, depending upon the visibility conditions, the PIC should decide whether to fly or not. If visibility is deteriorating, it is advisable to wait for the visibility to improve before resuming UAS operations. In doing so, the level of risk associated with operating a UAS near a building is greatly reduced. Another threat that can be linked to a LOS link is the loss of control of an aircraft. LOC of UASs can result in either the loss of communication from the controller or due to a mechanical failure. LOC of UAS when flying near a building can result in damage to property, cause injury to people, and result in the destruction of the UAS. To ensure that this does not happen, pre-flight UAS inspection and training can be implemented as barriers to keep the risk to an acceptable level. Pre-flight inspection can help the PIC identify anomalies in the UAS, particularly, for mechanical components. Pre-flight inspection can also help the PIC determine if the controller and the UAS are in perfect working condition for its desired operation. When the PIC decides to fly beyond LOS, it greatly reduces the PIC's ability to look out for obstacles that may be in the path of the UAS especially when flying near buildings. Flying beyond LOS also results in delayed action which further increases the risks associated flying near a building. To mitigate a growing risk from flying beyond LOS, the first and foremost barrier that needs to be implemented is flying in LOS. Flying in LOS not only helps the PIC maintain visual contact with the UAS, but it also helps the PIC monitor the surrounding environment to ensure that there are no obstructions present in the UAS' path.

Damage to a building and a UAS being destroyed or damaged are the two consequences that were identified from the bow-tie that could arise if the top event occurs. Damage to property was identified as a medium concern while damage or destruction of a UAS was identified as a major concern from the top event. If the top event is reached, that is, if a UAS is operated close to a building, then it can result in damage to a building. To ensure that this does not happen, one of the barriers that can be implemented by the PIC is to avoid flying near buildings. Procedural knowledge and flight plans are two additional barriers that can be placed between the top event and consequence to ensure that the consequence is averted even if the PIC decides to operate their UAS near a building. The flight plan should be developed in such a manner that it keeps the UAS as far away as possible from buildings. This includes that if the mission takes the UAS too close to a building or a structure, adequate procedures are available to handle emergencies. Similarly, to avert UAS damage or destruction, the PIC should avoid flying near buildings and have a good understanding of the procedures necessary to operate a UAS near a building.

Implications for Practice

The result from the study, in general, showed that the level of risks associated with operating a UAS in the NAS and near an airport is greatly influenced by the nature of the UAS' operation. From the NTSB results, it was evident that although the operations were carried out following the standard operating procedures (SOP) or were carried out under supervision, incidents still occurred. These incidents showed what is still missing in terms of risk assessment. This study particularly highlighted the errors in UAS operations which required a thorough risk assessment in order to mitigate risks. These errors included hard landings, aerodynamic stalls/spins, engine failures, and mid-air collisions. For the NTSB reports using qualitative content analysis, it was found that the organizational influence played a crucial role in the majority of the incidents. This shows that risk assessment needs to start from top level management. Several personnel issues, as well as organizational factors, were also identified as the holes in the Swiss Cheese Model. These issues included a lack of training to the personnel operating the UAS, delayed action, inadequate supervision among many others. After the completion of the analysis of the NTSB reports, bow-tie diagrams were used to highlight the most pertaining threats from the top events that were identified from the content analysis findings. These threats and their barriers when analyzed concerning the reports suggest that many of the barriers were already present at the time of the incident but did not mitigate the risks because the risk mitigation tool was not used. In order to provide adequate defenses in the Swiss Cheese Model, it is necessary that all the barriers are implemented. If these barriers are not implemented, even for a short time, it could result in a chain of events where the level of risk could increase over time.

The ASRS results showed that the majority of the PICs that operate UASs are unaware of the rules and regulations that govern flying UASs in the NAS or near airports. The majority of the reports filed had incidents related to airspace violation and UASs operating within five miles of an airport. Under

Part 107, UAS operations are strictly prohibited within five miles of an airport. A majority of ASRS reports were about UAS operating within five miles of an airport. FAA Part 107 also specifies that to operate in specific airspace class, the PIC needs ATC authorization. However, the results showed that the PIC was unaware of the requirement to get authorization from ATC. In one case, It was after the flight was completed that the PIC realized that they needed permission from ATC for the just-concluded flight. Other events identified from the results were operating near a moving automotive, flying at an unassigned altitude, excursion from assigned altitude, and flying close to a building. The ASRS database has reports that were voluntarily submitted, and it clearly shows that the general public or a person who flies a UAS for recreational use has very little knowledge of the regulation that governs the operations of UASs in the NAS or near airports. These factors play a significant role in increasing the risks associated with operating a UAS. Once the analysis was complete, the bow-tie diagram helped visually represent all the identified top events, the threats, and the consequences. Next, barriers were identified to mitigate risks arising from the threats and the top event. From the bow-tie diagram, it was clear that even if the PIC is flying a UAS for recreational use, the PIC needs to have a proper checklist in their possession to ensure that all aspects of the mission are checked and ready before the flight. The PIC needs to be well trained and should have a good understanding of the airspace classification and in which airspace class the UAS can be operated with and without authorization from ATC. Even though the FAA has multiple resources available for UAS operators, not everybody is aware of it. Such a situation creates a gap in information which does not help in conducting a thorough risk assessment for safe operations of UASs.

Recommendation for Future Studies

The current study had used qualitative content analysis to find the HFACS category of the most frequently occurring contributing factors and probable cause(s) for UAS incidents and accidents. From the results of the data analysis, the bow-tie diagram was used to identify the top events, the threats, and consequence that could arise from operating a UAS in the NAS and near airports. After the risk assessment, this study can be replicated to conduct incident analysis using IncidentXP which is part of the Bow-tieXP software package. In IncidentXP tripod, diagrams are used for incident analysis. Tripod beta diagrams are the next step towards conducting incident analysis to analyze the barriers that were implemented in the bow-tie diagram. When analyzing a scenario, the tripod data will help to understand what happened, how did it happen and why did it happen. In a tripod diagram, each identified barrier can be analyzed to see whether the barrier would be effective, ineffective, adequate, failed, or missing from the scenario. The tripod diagram can help the researcher determine and better understand the root cause of the scenario that is being analyzed. In addition to a thorough analysis of the incident barriers, analysis from tripod beta diagrams will identify the agent that triggered the incident and identify the object that had changed due to the incident. The object, for a given scenario, is anything that is tangible and is affected by the outcomes of the incident.

This study can also be replicated using a quantitative research methodology. For a quantitative study, a questionnaire can be developed and be distributed to commercial UAS operators or to students who actively fly a UAS for recreational purposes. The format of the questionnaire can be designed to ask participants basic questions about UAS operations. The questionnaire can include a question regarding what procedures are followed, pre-flight inspections, UAS checklists, fundamental FAA Part 107 regulations, and emergency procedures. A questionnaire would assist the researcher in identifying threats arising from UAS operations and assist in conducting risk assessments by analyzing the answers provided by the participants. From the results, the researcher would be able to provide adequate safety recommendations for safe UAS operations in the NAS and near airports. From a quantitative research methodology point of view, the study should have a large sample size to provide a thorough risk assessment.

This study can also be replicated in order to see the effectiveness of the barriers that were identified in the bow-tie diagrams. To see the effectiveness of barriers, a test flight in an open field could be planned to see whether the barriers assisted in mitigating risks. This can be done by asking the participants to fly their UAS in two different scenarios. The first scenario would be comprised of participants flying without implementing barriers from the bow-tie diagram. The second scenario would be comprised of participants being asked to fly their UAS but this time barriers would be implemented in their flying. Participants would first be asked to fly a predetermined course. This course could be anything from flying over an obstacle, flying beyond LOS, or failure situation such as a UAS component failure or loss of communication link. Results from both scenarios could be compared to evaluate which barrier worked in mitigating risks and which barriers failed to mitigate risks.

Conclusions

As previously mentioned in Chapter 1, the number of UAS sightings has drastically increased over the last few years. Even though these sightings did not result in serious incidents or accidents with multiple fatalities, these sightings cannot be taken lightly. As these sightings increase, the risks associated with operating UAS in the NAS and near airports is also increasing. From the current study, several factors involved in a UAS incident or accident were identified and analyzed. The study also identified several events that could potentially lead to incidents or accidents. These events, threats, and consequences were identified that could increase risks associated with their corresponding event. From the bow-tie diagram, it was evident that there were several factors in UAS operations that could increase the severity of threats and their corresponding consequences. These factors range from organizational influence, operating procedures, training, supervision, unsafe acts, and violation of regulations for operating a UAS in the NAS or near an airport. The study also highlighted that the majority of UASs flown for recreational purposes do not adhere to FAA Part 107 regulations.

Furthermore, in several reports, it was evident that the PIC was unaware of regulations that govern safe operations of UASs in the NAS and near airports. For all the threats and consequences, barriers were identified that need to be implemented to mitigate risks. The research also identified barriers that can be placed to ensure that consequences are not reached. The risk assessment showed that it is the sole responsibility of the PIC to ensure that their mission does not pose a threat to manned aircraft within their proximity, does not disrupt air traffic movement at an airport, does not pose any danger to people or property, and that the mission is carried out strictly under FAA Part 107 regulations. In order to do so, the PIC must have a thorough knowledge of their mission, what UAS they plan to operate, and have a checklist ready with them at all times. The checklist can be divided into two parts: Pre-flight checklist and post-flight checklist. The PIC is advised to plan their flight keeping in mind all of the crucial factors that can impact their mission and have an emergency plan ready to react on time. By implementing the barriers in the form of flight planning, training, airspace awareness training, UAS operational procedural knowledge, weather evaluation, pre-flight and post-flight inspections, flying in LOS, flying with a visual observer or under supervision, and adherence to FAA Part 107 regulation can mitigate risks when operating a UAS in the NAS and airports. In addition, it is also important that general awareness is created for the UAS operators. There are already multiple resources available both online and in hardcopy that provide all relevant information for operating UAS. However, these resources often go unnoticed and chances are there that the UAS operator may not refer to these resources before conducting their flight. As different industries have started using UAS for their operations, it is important that the

FAA and companies that manufacture UASs develop an outreach programs for UAS operators. These programs can be in form of webinars, seminars, or advertisments that inform new UAS operators about the regulations pertaining UAS operations. In this day and age of social media, there are several options available to the FAA and UAS manufactures like informative ads that can help spread awareness for UAS operations.

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Appendix A

ASRS Data Collection Form

Data Categories	ASRS Report Number:			
Flight Condition				
Flight Plan				
Flight Phase				
Airspace Class				
Contributing Factors				
Events	Anamoly	Detector	When Detected	Result
HFACS Category	Unsafe Acts	Preconditions for Unsafe Acts	Unsafe Supervision	Organisational Influences

Appendix B

NTSB Data Collection Form

Data Categories	NTSB Accident Number:			
Narrative Analysis				
Probable Cause and Findings				
HFACS Category	Unsafe Acts	Preconditions for Unsafe Acts	Unsafe Supervision	Organizational Influences