Safety Considerations for Operation of Different Classes of Unmanned Aerial Vehicles in the National Airspace System

by

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Abstract

There is currently a broad effort underway in the United States and internationally by several organizations to craft regulations enabling the safe operation of UAVs in the NAS. Current federal regulations governing unmanned aircraft are limited in scope, and the lack of regulations is a barrier to achieving the full potential benefit of UAV operations. Safety is a fundamental requirement for operation in the NAS. Maintaining and enhancing safety of UAVs is both the authority and responsibility of the Federal Aviation Administration (FAA). To inform future FAA regulations, an investigation of the safety considerations for UAV operation in the NAS was performed. Key issues relevant to operations in the NAS, including performance and operating architecture were examined, as well as current rules and regulations governing unmanned aircraft. In integrating UAV operations in the NAS, it will be important to consider the implications of different levels of vehicle control and autonomous capability and the source of traffic surveillance in the system.

A system safety analysis was performed according to FAA system safety guidelines for two critical hazards in UAV operation: midair collision and ground impact. Event-based models were developed describing the likelihood of ground fatalities and midair collisions under several assumptions. From the models, a risk analysis was performed calculating the expected level of safety for each hazard without mitigation. The variation of expected level of safety was determined based on vehicle characteristics and population density for the ground impact hazard, and traffic density for midair collisions.

The results of the safety analysis indicate that it may be possible to operate small UAVs with few operational and size restrictions over the majority of the United States. As UAV mass increases, mitigation measures must be utilized to further reduce both ground impact and midair collision risks to target levels from FAA guidance. It is in the public interest to achieve the full benefits of UAV operations, while still preserving safety through effective mitigation of risks with the least possible restrictions. Therefore, a framework was presented under which several potential mitigation measures were introduced and could be evaluated. It is likely that UAVs will be significant users of the future NAS, and this thesis provides an analytical basis for evaluating future regulatory decisions.

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Contents

List of Figures

List of Tables

Acronyms and Abbreviations

AC	Advisory Circular
AIM	Aeronautical Information Manual
AMA	Academy of Model Aeronautics
AOPA	Airplane Owners and Pilot's Association
ASRS	Aviation Safety Reporting System
ASTM	American Society for Testing Materials
ATM	Air Traffic Management
COA	Certificate of Authorization
DHS	Department of Homeland Security
DSA	Detect, Sense, and Avoid
ELS	Expected Level of Safety
ERAST	Environmental Research and Sensor Technology
ETMS	Enhanced Traffic Management System
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
GA	General Aviation
HALE	High Altitude, Long Endurance
IFR	Instrument Flight Rules
LIDAR	Laser Radar
LOS	Line of Sight
MALE	Medium Altitude, Long Endurance
MTBF	Mean Time between Failures
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NTSB	National Transportation Safety Board
OSD	Office of the Secretary of Defense
OTH	Over the Horizon
RC	Radio-controlled

RF	Radio Frequency
ROA	Remotely Operated Aircraft
RTCA	Radio Technical Commission for Aeronautics
RVSM	Reduced Vertical Separation Minimums
SFAR	Special Federal Aviation Regulation
SSH	System Safety Handbook
TCAS	Traffic Collision and Avoidance System
TLS	Target Level of Safety
UAV	Unmanned Aerial Vehicle
UNITE	UAV National Industry Team
USC	United States Code
USICO	UAV Safety Issues for Civil Operations
VHF	Very High Frequency
VFR	Visual Flight Rules

Chapter 1

Introduction

1.1 Objective

Unmanned Aerial Vehicles, or UAVs, are emerging as a new type of aircraft to be operated in the National Airspace System (NAS). Recent technological advancements and increased military utilization have proven the operational viability of UAVs and made them attractive for a wide range of potential civil and commercial applications in the United States. Federal aviation regulations did not anticipate the operation of unmanned aircraft, and the lack of regulations is an impediment to achieving the full potential public benefit that UAVs may offer. The Federal Aviation Administration (FAA) has identified the need to develop policies and establish procedures and standards to enable the future operation of UAVs in the NAS [1,2]. Recognizing that safety is a fundamental requirement for operating in the NAS, a safety-focused approach was taken in this thesis is to inform future civil UAV policy-making. A systematic analysis of the safety considerations for operating different classes of UAVs in the NAS was performed. The goal of the analysis is to understand how to achieve the potential public benefit of UAV operations, while also protecting the public from harm.

1.2 Motivation

The employment of UAVs by the United States armed forces has been rapidly increasing. A Department of Defense report on UAV reliability [3] included the cumulative flight hours from 1987 to 2002 for three UAV types: the *Pioneer, Hunter, and Predator*, aggregated shown in the first part of Figure 1. Since the publication of the report, UAVs have been deployed in significant numbers in support of recent conflicts. In addition, the Army began operations of the *Shadow* tactical UAV, and the Air Force deployed the *Global Hawk*. In light of these recent events, the operational trends after 2002 have also been estimated and included in Figure 1. The estimates are based on reported operational milestones from manufacturers and the press[1] . Based on these estimates, U.S. military utilization of UAVs has been growing exponentially since 1988, and doubled from 2002 to 2004.

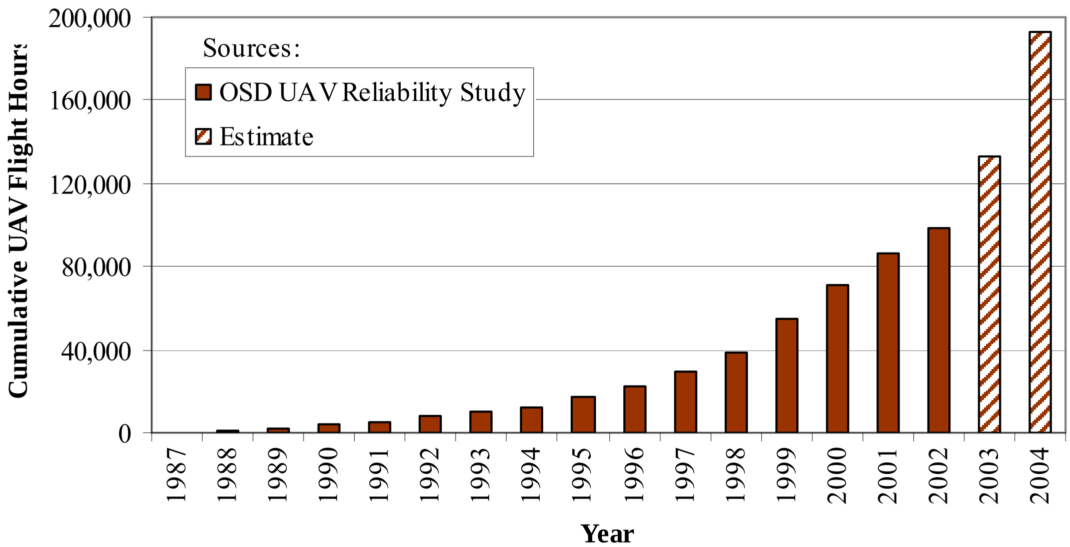

Figure 1: U.S. Military UAV Flight Hours

Military utilization of UAVs has proven the operational viability of a diverse set of unmanned aircraft and has led to significant demand for the use of UAVs for civil and commercial applications in domestic airspace [7]. A broad range of UAVs have been used to perform both civil and military missions. Four examples of currently operated civil and military UAVs are shown in Figure 2. The *APV-3* and *Helios* UAVs have been used to demonstrate civil applications by the National Aeronautics and Space Administration (NASA). The *Dragon* Eye and *Global* Hawk have been employed by the U.S. Army and Air Force respectively in recent conflicts. While the UAVs have been divided between civil and military applications in Figure 2, the distinction is not necessarily absolute. Airframes can be utilized for multiple applications.

[1] In 2004, the *Predator* reached an operational milestone of 100,000 hours [4], the *Hunter*, 50,000 hours [5], and the *Shadow* 10,000 hours [6].

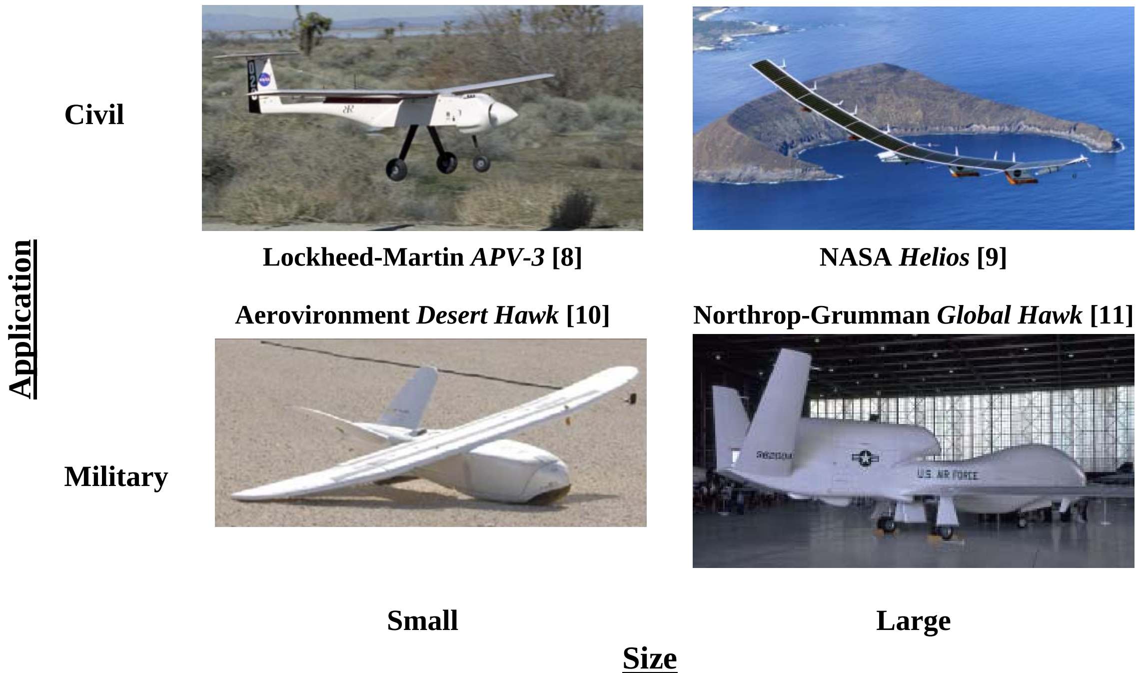

Figure 2: Examples of Current Civil & Military UAVs

There is a significant latent demand for the ability to operate UAVs for a variety of applications in civil airspace. However, a lack of federal regulations has been a barrier to achieving routine operation in the NAS. Current federal rules governing unmanned aircraft are limited in scope to recreational model aircraft, unmanned balloons, kites, and rockets. Any UAV flight in the NAS that is not governed under the existing rules must be individually approved through a Certificate of Authorization (COA), a process for exemption from current regulations. The process was originally utilized for non-routine military UAV operations in civil airspace. It is therefore lengthy and inefficient when applied to many civil operations, requiring detailed review and approval by FAA authorities for each individual flight to be conducted in the NAS.

The combined action of regulatory agencies, UAV manufacturers, and research into enabling technologies is expected to result in a significant increase in civil UAV operations in the future. The character and scope of UAV operations will depend upon the regulatory requirements placed on civil UAV systems. With their potential utility for a variety of applications, it is in the public interest to achieve the full potential benefit of UAV operations, while maintaining an acceptable level of safety.

1.3 Approach

The goal of this thesis is to systematically examine the safety implications of the operation of different classes of UAVs in the NAS. To accomplish this goal, it is first necessary to provide background on the military history of UAV operations and current efforts to effect civil UAV regulations. Next, the structure and procedures of the National Airspace System are examined, with an emphasis on how air traffic management functions of vehicle control and traffic avoidance are currently performed and may be implemented for a variety of UAV architectures. The performance characteristics of several current UAVs are examined, and a general classification scheme differentiated primarily by mass is introduced. Finally, the regulatory bases for UAV safety are examined, including the federal legal mandate and authority of the FAA for UAV safety and current rules governing model aircraft, unmanned balloons, kites, and rockets, and the COA process.

To understand the safety implications of future UAV operations in the NAS, a safety analysis was performed according to FAA system safety guidelines. A model was developed to describe the estimated rate of occurrence of two critical hazards to the public due to UAV operations: ground impact and midair collision. From the results of the model, the implications for potential low risk UAV operations were analyzed. Potential approaches for controlling and mitigating the risk were identified and discussed as part of a general framework for evaluating their effectiveness, and recommendations were made on the potential requirements for integrating different classes of UAVs in the NAS.

Chapter 2

Background

2.1 Expanding Role of Military UAV Operations

Unmanned Aerial Vehicles (UAVs) were first used by the military in 1917 when the Navy commissioned the design of an "aerial torpedo" for use against German U-boats. A contract was awarded to the Curtiss Aeroplane Company, and the airplane was named the *Speed-Scout*. According to a history of unmanned aircraft [12], the Curtiss *Speed-Scout* was designed to be launched from Navy ships carrying a 1,000 lb. payload and to be stabilized by an autopilot. The *Speed-Scout* suffered several failures before it achieved its first successful flight on March 6, 1918, marking the first flight of a UAV.

The early role of UAVs was not much different from the role of the *Speed-Scout*. Unmanned aircraft continued military service as expendable weapons delivery platforms or as aerial targets. As technology matured, UAVs began to be used increasingly as military reconnaissance assets. The *Firebee* was the first notable UAV to be used routinely by the U.S. as a military reconnaissance asset, flying 3,435 sorties during the Vietnam Conflict [13]. *Firebee* UAVs were launched on preprogrammed routes, returning to a designated area where their payload was recovered to analyze the intelligence gathered.

The Israeli Air Force pioneered the use of modern unmanned aircraft in the 1970s and 80. In contrast to previous operations, Israeli UAVs were controlled and the intelligence monitored in real time. The success of this type of operation led the U.S. military to acquire the Israeli-designed *Pioneer* [14] in 1986. The military continued acquiring other UAV types and made extensive use of UAVs in the first Gulf War, flying 520 sorties during the conflict [13].

UAVs continued to demonstrate their utility in recent conflicts. The need for UAV reconnaissance was so urgent in Afghanistan, that the *Global Hawk* was rushed into service while still in a developmental stage of acquisition. Real time vehicle control and near-instantaneous dissemination of information has also become routine. In *Global*

Hawk's continued service in the second Iraq conflict, portions of the mission were controlled via satellite from Beale AFB in California [15], far removed from the theater of operations.

The utility of UAVs has also been reflected in increased military procurement rates. The armed forces' inventory of UAVs has been steadily increasing, with 90 vehicles in inventory in 2001 [13], 163 in 2003[14], and projections of 249 by the end of 2007 [14]. Branches of the U.S. military currently operate five large UAV types – *Global Hawk*, *Predator*, *Pioneer*, *Hunter*, *and Shadow*. Individual military units also operate smaller UAVs, such as the 4 lb. *Raven & Dragon Eye*, 7 lb. *Desert Hawk*, 10 lb. *Pointer*, and 30 lb. *Scaneagle*.

The U.S. military was one of the early proponents for UAV operations in the NAS, for the purpose of repositioning aircraft between bases. The current COA procedures were initially formulated for military UAV operations[1], and considerations for NAS operations were first introduced into the design of the *Global Hawk* with the inclusion of the Traffic Collision and Avoidance System (TCAS) [16]. Military UAVs are likely to be used initially as platforms for civil and commercial applications, because military demand drives the majority of the current market for airframes.

The safety of UAVs in military operations has been improving significantly. Combined yearly accident rates for the *Pioneer*, *Hunter*, and *Predator* UAVs from a Department of Defense study on UAV reliability [13] are compared to historical accident rates for manned military and civil aviation from a variety of sources[2] in Figure 3. There are several differentiating factors in design and operation between military and civil aircraft that can confound a direct comparison of accident rates[3]. However, a comparison of the trends in accident rates is noteworthy. UAV accident rates have been decreasing rapidly since the introduction of modern UAV operations in U.S. military service in

[1] The COA procedures are outlined in FAA Order 7610.4 *Special Military Operations*
[2] General and Commercial Aviation accidents statistics were reported by the National Transportation Safety Board [17]. Air Force Aviation Class A mishap rates were published in an Air Force Safety Center presentation [19]. UAV are included in the category of Air Force Aviation
[3] Apart from differences in operation, accidents are also defined differently. The NTSB defines an accident as any time a fatality or serious injury occurs or there is "substantial damage" to an aircraft. The military defines a Class A mishap based on the occurrence of a fatality, complete loss of an aircraft, or damage to government property in excess of $1 million [20]

1987. A projection of the current trend would cause UAVs to approach the current accident rates in general aviation and manned military aviation.

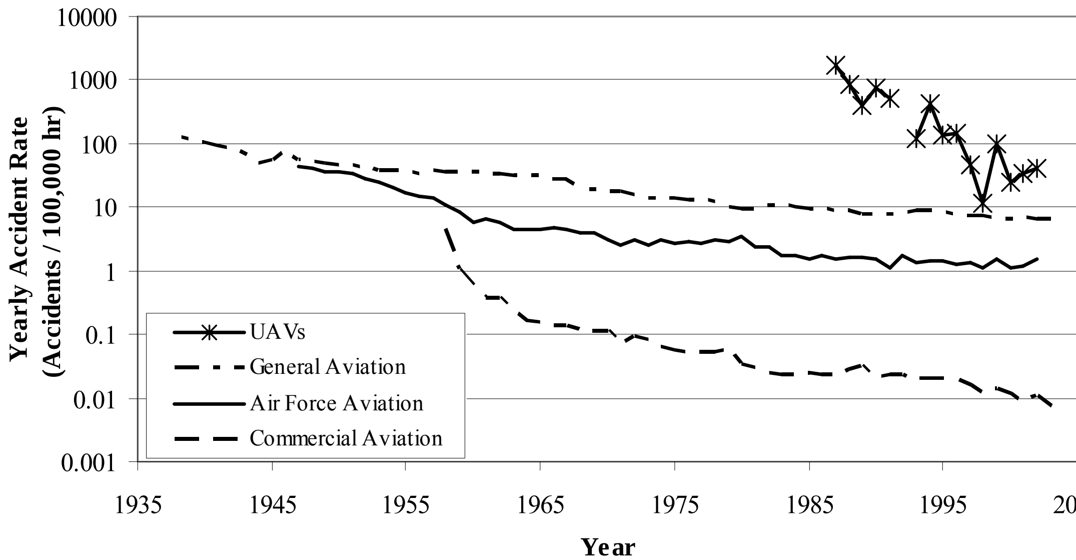

Figure 3: Comparison of Accident Rate Trends between Several Categories of Aircraft

2.2 Effort Toward Civil UAV Operations

The success of recent military UAV deployments, and the desire for expanded markets by UAV manufacturers has led to an increasing interest, both in the United States and abroad, for performing a variety of missions in civil airspace. Several efforts to demonstrate civil applications, craft new UAV regulations, and improve the safety of UAVs are currently underway. The efforts are likely to result in the emergence of significant future UAV operations in the NAS.

There is a broad range of potential civil and commercial applications for which UAVs are attractive platforms. Several applications for UAVs that have been proposed or demonstrated are summarized in Table 1. The list is not comprehensive, but is meant to highlight the broad range of potential applications considered. In the United States, the National Aeronautics and Space Administration (NASA) began demonstrating civil UAV operations under the Environmental Research and Sensor Technology (ERAST) program. In ERAST, NASA partnered with several UAV manufacturers to develop and demonstrate UAVs for earth science missions. NASA continues to develop technology and demonstrate UAV operations for a range of potential applications through research programs [21] and the formation of a UAV applications center at NASA Ames [22].

Table 1: Attractive UAV Applications

Remote Sensing • Pipeline Spotting • Powerline Monitoring • Volcanic Sampling • Mapping • Meteorology • Geology • Agriculture Disaster Response • Chemical Sensing • Flood Monitoring • Wildfire Management	Surveillance • Law Enforcement • Traffic Monitoring • Coastal/ Maritime Patrol • Border Patrol Search and Rescue Transport • Cargo Transport Comm Relay • Internet • Cellular Phone	Delivery • Firefighting • Crop Dusting • Package Delivery Entertainment • Cinematography • Advertising Broadcast • Television/ Radio

Recognizing the lack of regulations as a barrier to routine operations, there are several efforts underway both in the United States and internationally craft UAV regulations and to define procedures to enable routine UAV operations in civil airspace. In the United States, the push for new regulations is being led by a consortium of UAV manufacturers, NASA, and the Department of Defense, known as Access Five, with the goal of achieving routine operations for high altitude, long endurance (HALE) UAVs [7]. Parallel efforts are underway to develop consensus-based UAV standards through separate committees convened by the American Society of Testing Materials (ASTM) [23] and the Radio Technical Commission for Aeronautics (RTCA) [24,25]. The purpose of the committees' efforts is to advise future FAA UAV Regulations.

International regulatory efforts are also underway. In Europe, the USICO project (UAV Safety Issues for Civil Operations) funded by the European Commission is also focused on achieving civil and commercial UAV operations in European airspace. The United Kingdom has published advisory material on operating UAVs in civil airspace [26], and Australia has enacted regulations allowing certification of several classes of UAV operations [27].

Chapter 3

Key Issues in UAV Operations in the NAS

The National Airspace System (NAS) has evolved to support safe operation and equitable access to resources by a diverse range of users. The procedures, performance, and architecture of the NAS have evolved primarily to support manned operations. Therefore, when considering the potential unmanned aircraft, there are several issues related to the ability of UAVs to integrate with the other users of the NAS according to established procedures and architecture.

The purpose of this chapter is to examine the safety issues in UAV operations in the NAS. First, the current airspace and operational rules of the NAS are introduced. Next, the functioning of the air traffic management system is investigated, and potential UAV architectures for control and traffic surveillance are introduced. Finally, UAV performance capabilities are discussed, with implications for integration in the NAS and to define general classifications in the following safety analysis.

3.1 NAS Overview

The National Airspace System (NAS) is the collection of procedures, regulations, infrastructure, aircraft, and personnel that compose the national air transportation system of the United States. The purpose of the system is to safely facilitate air transportation and provide equitable access to both air and ground-side aviation resources. The infrastructure of the NAS has evolved to support navigation and air commerce of manned aircraft. Elements of the infrastructure include federal airways, radio navigational aides, airports, surveillance, and air traffic control service facilities. The system is governed by United States law and the federal aviation regulations, which govern both the design and operation of aircraft within the system, as well as structures on the ground that affect air navigation. The basis of the FAA's authority over UAVs will be further examined in Chapter 4.

3.1.1 Visual and Instrument Flight Rules

There are two different modes of flight rules governing operations in the NAS: visual flight rules (VFR), and instrument flight rules (IFR). The purpose of the distinction between VFR and IFR is to require different procedures for navigation, landing, and separation of traffic depending upon the availability of visual cues to the pilot of an aircraft. In visual meteorological conditions (VMC), there is sufficient visibility allowing the pilot to fly the aircraft through outside cues and to see and avoid other aircraft. In contrast, in instrument meteorological conditions (IMC), reliance on onboard instrumentation for navigation is required, as well as procedural separation from other traffic through air traffic control. To fly under IFR, pilots must receive additional training and certification, and aircraft must have additional instrumentation.

The distinction between visual and instrument flight rules is most relevant to UAV operation in the context of traffic avoidance. Visual flight rules can serve as one foundation for a required level of performance of UAV sensors. By this potential standard, the UAV's sensors would be required to replicate the performance and functionality of the human eye, and the total system to be equivalent in design to a pilot's presence in the cockpit.[1] The distinction between VFR and IFR is also important when considering the visibility of UAVs to other aircraft, and how other pilots might be required to identify and avoid collisions with the UAV.

3.1.2 Airspace Classifications

Airspace over the United States is divided into restricted, controlled, and uncontrolled airspace. The airspace where operations are under the direct control of the FAA is outside of restricted airspace and is generally referred to as civil airspace. The FAA has divided civil airspace over the United States and within 3 nm of the coast into six different classes, which are shown in a simplified diagram in Figure 4. The classifications separate regions of the airspace by the level of service provided by air traffic control, the type and density of operations conducted in the airspace, and the level of safety required [29]. Airspace classification has the effect of procedurally separating

[1] FAA Order 7610.4 [28] requires the UAV applicant to provide a method for traffic avoidance at an "equivalent level of safety, comparable to see-and-avoid requirements for manned aircraft."

air traffic, and therefore procedures for different UAV classes are likely to depend upon the airspace in which they operate.

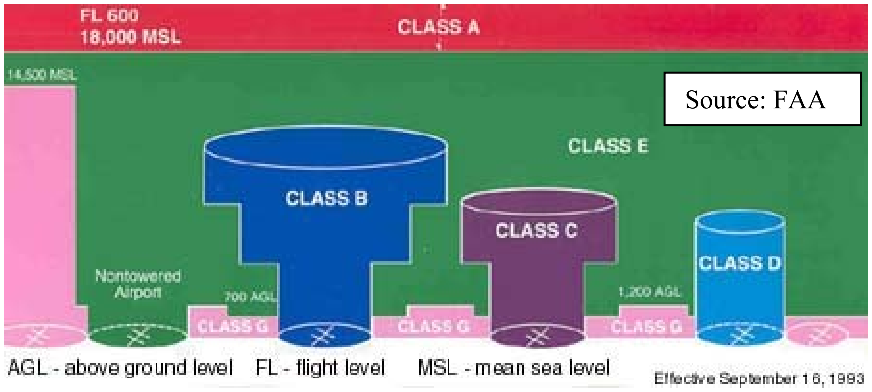

Figure 4: FAA Airspace Classes

Classes A, B, C, D, and E are referred to as controlled airspace, and Class G is uncontrolled airspace. Each class has defined boundaries and weather minimums for VFR flight which are described in the FAA's Aeronautical Information Manual (AIM) [29], and on aeronautical navigational charts. A detailed discussion is beyond the scope of this thesis. The important aspects of airspace classification relevant to UAV operations are the general restrictiveness of each airspace class, communications and entry requirements, and separation services provided by air traffic control. These parameters are summarized in Table 2, with information from the FAA [30].

Table 2: Summary of Characteristics of Controlled Airspace

Airspace Class	Communications	Entry Requirements	Separation Provided	Minimum Pilot Qualifications
A	Required	ATC clearance	All aircraft	Instrument Rating
B	Required	ATC clearance	All aircraft	Private or Student Certificate (location dependent)
C	Required	Two-way communications prior to entry	VFR from IFR	Student certificate
D	Required	Two-way communications prior to entry	Runway operations	Student certificate
E	Not required for VFR	None for VFR	None for VFR	Student certificate
G	Not Required	None	None	Student certificate

From the requirements, it can be seen that the restrictiveness of airspace decreases in alphabetical order from Class A to Class G. The separation services provided by air traffic control also vary as the restrictiveness of the aircraft decreases, based on the density and type of operations in the class of airspace.

3.2 Air Traffic Management System

Air traffic management (ATM) is the process by which air traffic control (ATC), separates and controls air traffic in the NAS. The ATM architecture varies depending upon the separation services provided by air traffic control, as discussed in the previous section. In considering UAV operations, there are two key technological areas that differentiate UAV architectures within the ATM system: vehicle control, and traffic surveillance and avoidance. By removing the pilot from direct operation of the vehicle, UAVs introduce the potential for different control and traffic surveillance methods that still preserve the overall function of the ATM system. This section will introduce the current system, define general UAV ATM architectures, and then discuss specific architectures that have been utilized or proposed.

3.2.1 Current System

A simplified diagram of current commercial aircraft in the ATM system, adapted from Hansman, et. al. [31], is shown in Figure 5. The notation is based on the semi-structured decision framework [32] developed to represent human/automation allocation in mixed-control systems. For the purposes of this thesis, blocks in the diagram represent controllers in the system, with the dashed blocks representing surveillance processes that have been decomposed to specific processes inside the boundary. Information flows and interfaces between processes are also included.

In the current ATM system of Figure 5, Air Traffic Control surveils the position of aircraft, and separates aircraft by issuing commands to the pilot through VHF radio. The pilot controls the aircraft through the aircraft systems at varying levels of control and receives feedback through cockpit displays. Onboard surveillance of other air traffic is also available through two sources. First, direct sensing of other traffic through visual search is possible with the pilot onboard the aircraft. The second source is the Traffic Collision and Avoidance System (TCAS), which is required equipage for most transport aircraft. This decision-aiding system receives transponder signals from cooperative traffic in the vicinity. The cooperative traffic surveilled by the system encodes altitude information in the transponder signals. The transponder signals are then used to localize the traffic and report the traffic's altitude to the system. If a conflict is detected, TCAS advises the pilot on an appropriate vertical avoidance maneuver.

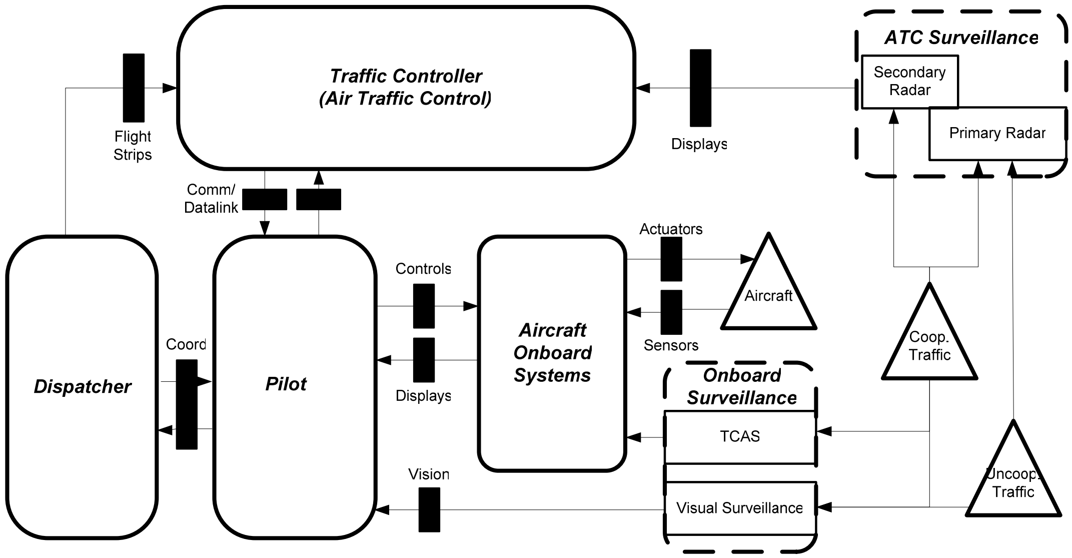

Figure 5: Simplified Diagram of Current Air Traffic Management System

3.2.2 General UAV System

UAVs present several new opportunities to utilize advanced technology for avoiding traffic, controlling the aircraft, and communicating with air traffic control. UAVs will also have potentially different control architectures than the current ATM system. The general UAV control architecture, with several potential surveillance paths and control interfaces is shown in Figure 6.

In comparison to the manned aircraft process in Figure 5, in UAV operation there is a physical separation between the operator and aircraft. This separation necessitates the use of a link between operator and vehicle, which has associated bandwidth and latency limitations. The separation also necessitates a separate physical control environment on the ground, shown by the ground station. UAVs typically have the addition of a sensor operator that controls the payload of the UAV to receive information from the environment, and may utilize an operational controller to coordinate the activities of the UAV.

The two key areas of technology that are useful in differentiating UAV architectures are the control capability of the UAV onboard systems and the surveillance path to other traffic. The control capability of the onboard systems is referred to as the level of autonomy of the UAV. In Figure 6, the task allocation of different elements of the system, as well as the information transmitted across interfaces will vary depending upon the capability and mode of the automation. The path of surveillance information will also define the architecture of the system. An important distinction must be made between the surveillance of cooperative traffic, which is capable of broadcasting its position through a transponder, and noncooperative, which does not broadcast a transponder signal. Surveillance technologies are defined by their ability to detect the two different traffic types. Several interfaces are possible between controllers in the system. The presence of an interface for specific types of operation depends upon the technology available and the performance requirements of the operation. Specific examples will be discussed in the next section.

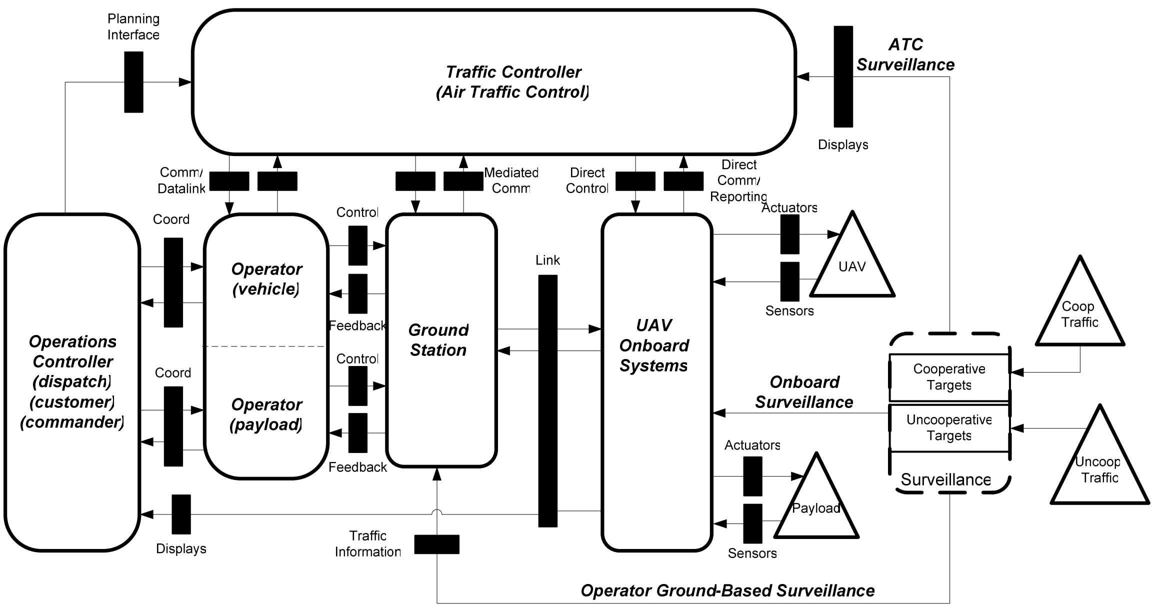

Figure 6: General UAV Air Traffic Management System

3.2.3 Potential UAV Architectures

There is a broad range of potential architectures that fit within the general framework of Figure 6. When referring to specific architectures, distinctions must be made along the two previously identified technology areas: UAV onboard system control capability (e.g. autonomy) and traffic surveillance source. Categories of UAV onboard autonomy capabilities can be defined in the context of vehicle operation, which refers to the task of planning, navigating, and piloting the vehicle. Potential categories of vehicle control are outlined in Table 3, modified from the Air Force Research Lab taxonomy for levels of vehicle autonomy [33], along with a description of how UAV control is executed under each category. The categories are ordered in decreasing functional capability of the UAV onboard systems.

Table 3: Categories of UAV Control

Category of Vehicle Control	Description
Autonomous & Adaptive	The UAV is controlled completely by UAV onboard systems without intervention by an operator or use of a ground station. The UAV has the ability to replan during the flight to account for changes in the environment or new objectives. The UAV may also have the capability to communicate with other controllers in the system.
Monitored	The UAV operates autonomously, while an operator monitors feedback from the UAV. The operator does not have the ability to control the UAV, but could potentially take control actions through other actors in the system.
Supervisory	Low level control is executed by the UAV systems onboard the UAV or ground station. The operator remains engaged in the control loop executing higher level control of the UAV's trajectory or state.
Autonomous & Non-Adaptive	The UAV has the ability to execute pre-programmed actions without input from an operator, but does not have the ability to change the plan during flight or adapt to external disturbances.
Direct	The operator directly controls the UAV control surfaces, mediated by the link between the UAV and ground station

Current research on UAV autonomy has been conducted in several areas, for a general review, see Clough [34]. The majority of the research focuses on extending UAV capabilities to robustly form and execute plans with minimal human input. This "higher level" autonomy research is primarily performed by the military to improve battlefield capabilities and reduce the number of operators required to control one or multiple UAVs. Additional research is conducted at an enabling level to improve technology and methods for a given task, with application to several domains. Research included in this category is image processing research for collision avoidance sensing, voice recognition for control, and trajectory optimization.

The second key technological area that defines UAV architectures is the source of traffic surveillance. Methods of traffic avoidance will vary depending on the source and capabilities of the surveillance and the responsibility for maintaining traffic separation. Three potential surveillance paths are present in Figure 6: onboard surveillance, ground-based surveillance, and ATC surveillance sources. Descriptions of several types of technology utilized for surveillance that fit these categories are included in Table 4. Surveillance by a chase aircraft is a special surveillance category that does not fit into the three potential paths described above. It is a special case, with an additional manned aircraft flying formation with the UAV and performing the required surveillance functions for the UAV.

Table 4: Sources of Traffic Surveillance

Source of Traffic Surveillance	Description
ATC Ground-Based Surveillance	The current primary and secondary radars utilized by ATC. Update rates vary depending upon the location of the radar. Primary radar is capable of surveilling all traffic, but secondary radar relies on transponder signals to provide altitude information to air traffic control..
Operator Ground-Based Surveillance	Individual radar or other surveillance source located on the ground in the area where the UAV is operated. Provides surveillance of other air traffic to the UAV operator or transmitted to the UAV's onboard systems.
Sight	Direct surveillance of other air traffic by the operator's line of sight on the ground. Requires the UAV to be operated close to the operator and also within the operator's line of sight.
Onboard (noncooperative)	Surveillance source onboard the UAV that has the capability to detect noncooperative targets. The detection can be accomplished through active transmission and reflection of energy, or through passive means.
Onboard (cooperative)	Surveillance source onboard the UAV that is only capable of detecting cooperative traffic through broadcast signals from the other traffic. The broadcast may provide horizontal or vertical information, or both.
Chase aircraft	An aircraft flying in formation with the UAV provides the capabilities of a manned aircraft with the operation of the UAV.
Broadcast	No traffic surveillance is provided to the UAV, but the UAV could transmit its position to other aircraft or air traffic control.
Visibility	No traffic surveillance is provided to the UAV, but the UAV is made highly visible to facilitate avoidance by other aircraft

The majority of current UAV-related research efforts are focused in the area of collision avoidance. Collision avoidance research is categorized primarily by its applicability to cooperative or noncooperative traffic. In the category of avoidance of cooperative threats, the Air Force has commissioned a study to certify the Traffic Collision and Avoidance System (TCAS) for use on the *Global Hawk* UAV [16]. The recertification is necessary because TCAS was not originally designed with high lateral fidelity, and the *Global Hawk* has significantly different climb characteristics than most aircraft, and therefore generates different midair collision encounter scenarios than originally envisioned in the certification of TCAS. For sensing of noncooperative traffic, research on several sensors has been conducted, with an emphasis on reduced weight. Specific technologies include infra-red sensors [35], optical sensors, and laser radar (LIDAR).

Central to the importance of UAV surveillance technologies is the ability to meet or exceed the performance of current manned aircraft in traffic detection. In 2003, NASA performed a flight test between a UAV and several other aircraft with varying performance capabilities [36]. The test evaluated two systems for traffic avoidance: a radar mounted on the UAV to detect noncooperative targets and a traffic advisory system, for cooperative targets. The flight test also informally tested the pilot's acquisition capabilities. The conclusions from the flight test were mixed. Only the traffic advisory system was sufficient for all encounter scenarios. The radar had a limited range of 4 miles, which did not detect targets with enough time to maneuver and avoid a collision. The test pilots reported that their effective range for picking up an aircraft was 1-1.5 nm. Additional research has focused on sensor performance levels to maintain an equivalent level of safety to current midair collision rates [37]. This line of investigation also found that the human eye was inadequate to detect and prevent collisions under several potential scenarios. The results show that even with current surveillance sources, some collisions may not be preventable, and even limited sensors perform better than the human eye.

3.2.4 Architectures of Example UAV Operations

A variety of different architectures have been utilized by current unmanned aircraft operations, such as weather balloons or model aircraft, for which the governing rules and regulations will be discussed in Chapter 4. In Table 5, the surveillance and control methods for several examples of current and proposed future concepts have been included, along with a description of their operation. For each system, the architecture has also been drawn according to the general architecture presented in Figure 6, with elements grayed out that are not present in the system.

Table 5: Control and Surveillance Methods for Example UAV Systems

UAV System	Control/ Surveil. Method	Description	Shown in
Model Aircraft	Direct / Sight	Model aircraft are operated by radio-control, and operators are responsible for maintaining visual contact with their aircraft and separation from full-scale aircraft [38]	Figure 7
Weather Balloon	Monitored / Visibility	Weather balloons are released into the atmosphere, and are not controlled after release. They are required to be visible to air traffic control through position reports or radar returns, and visible to other aircraft for avoidance	Figure 8
Global Hawk, Access Five Concept	Supervisory / ATC; Cooperative Onboard	The Air Force operates the global hawk in Class A airspace through supervisory control and air traffic control collision avoidance. This is the first step of access five plans for HALE operations in the NAS [7]	Figure 9
NASA Vineyard Demonstration	Supervisory/ Individual Ground Radar	A recent NASA demonstration utilized local radar to avoid traffic in the NAS while performing an agricultural surveillance mission over a vineyard in California [39]	Figure 10
Autonomous & Adaptive Concept	Autonomous & Adaptive / ATC; Uncoop Onboard	As yet unrealized concept. The UAV would be capable of communicating and complying with ATC instructions, and actively avoiding other aircraft. A customer would receive information directly from the UAV.	Figure 11

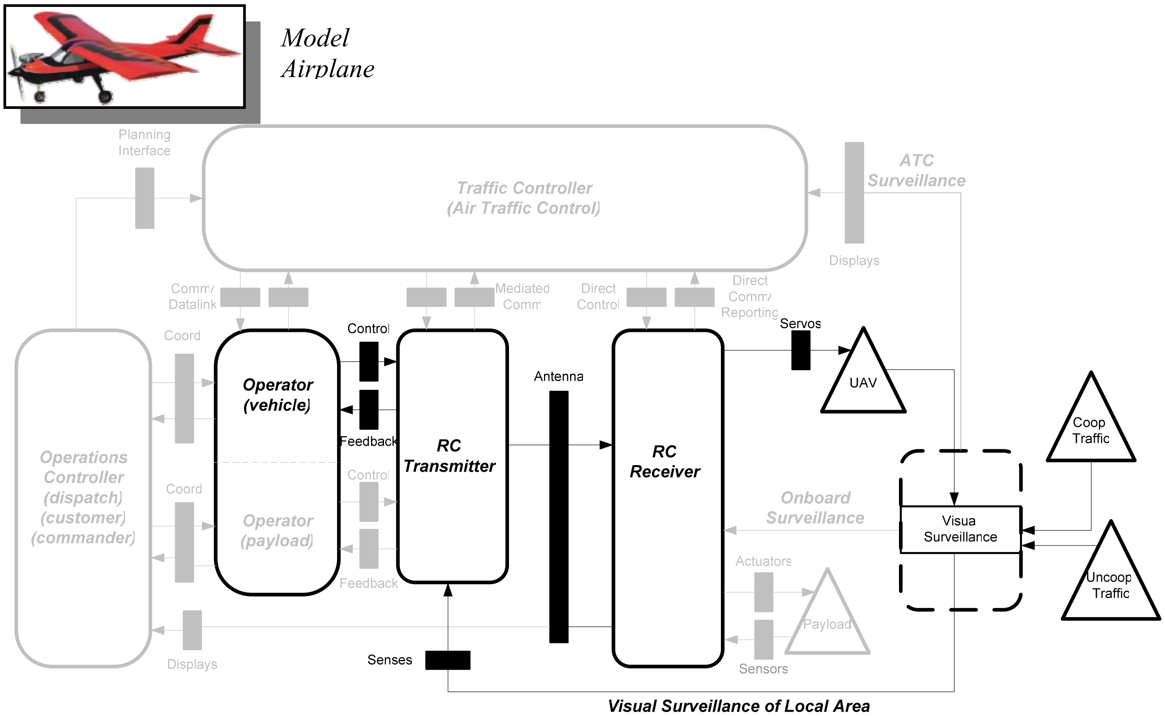

Figure 7: Radio-Controlled / Model Aircraft Operation in the NAS

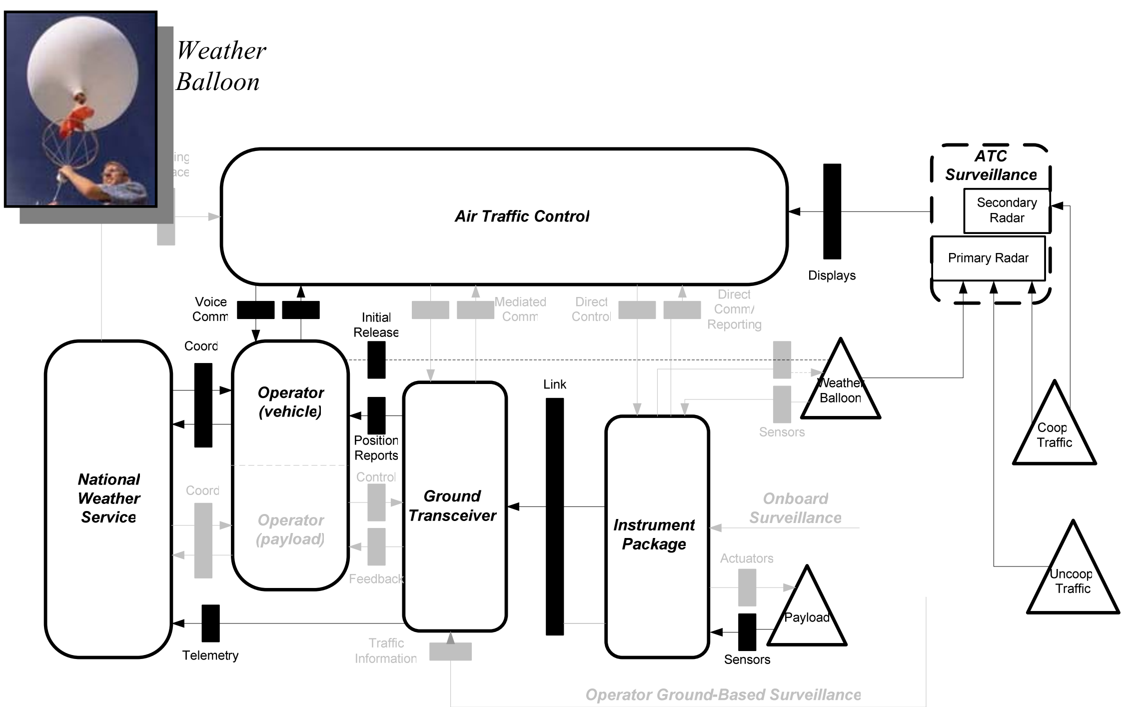

Figure 8: Weather Balloon Operation in the NAS

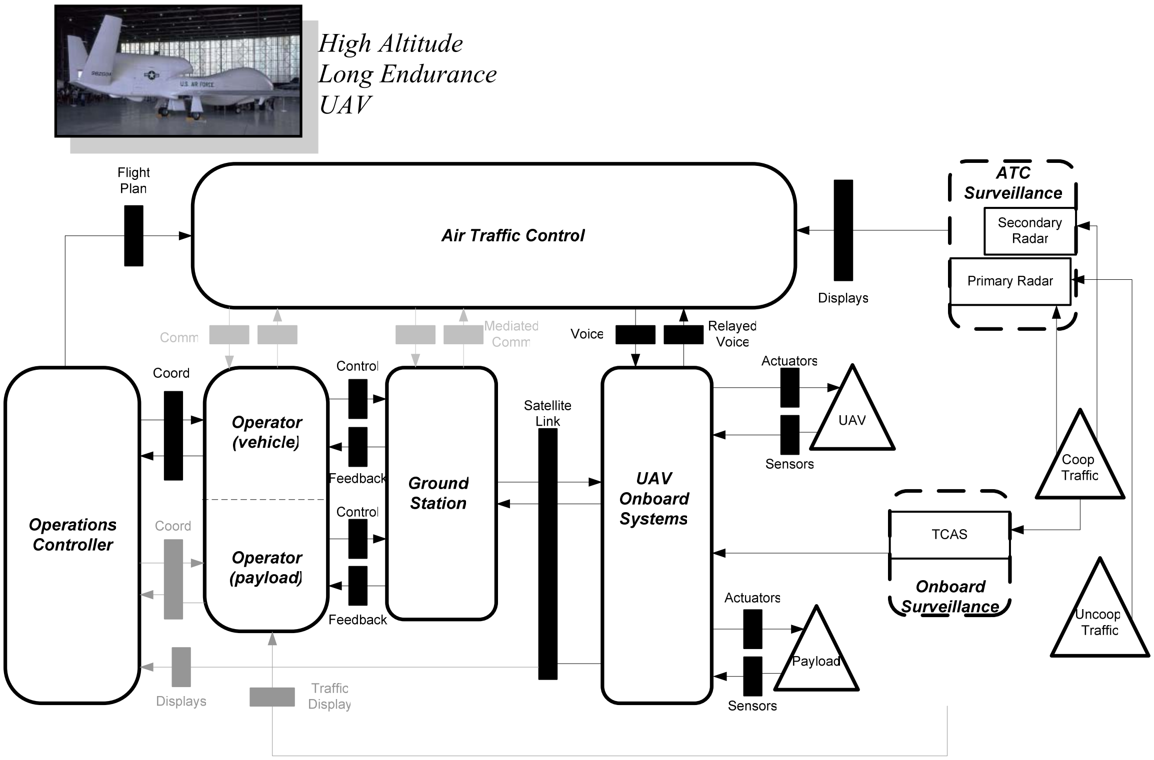

Figure 9: HALE/ Access 5 Concept of Operation

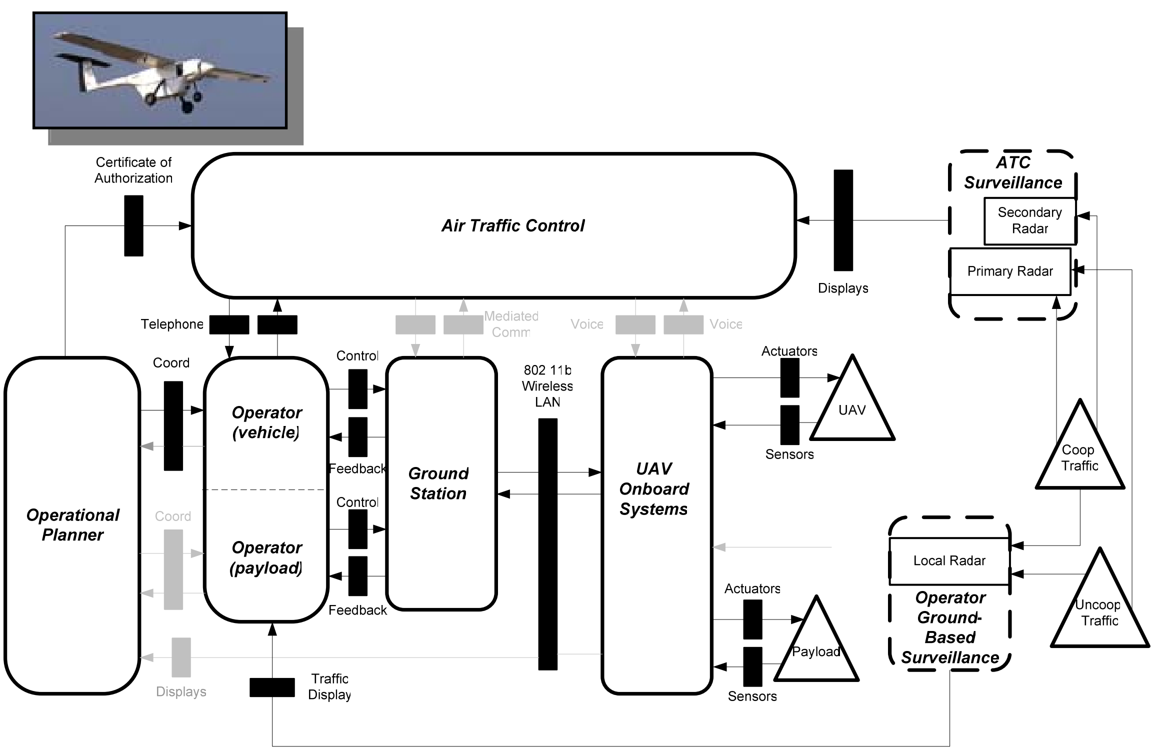

Figure 10: NASA Vineyard Demonstration Mission

Rendering of NASA 21st Century Aerial Vehicle Concept

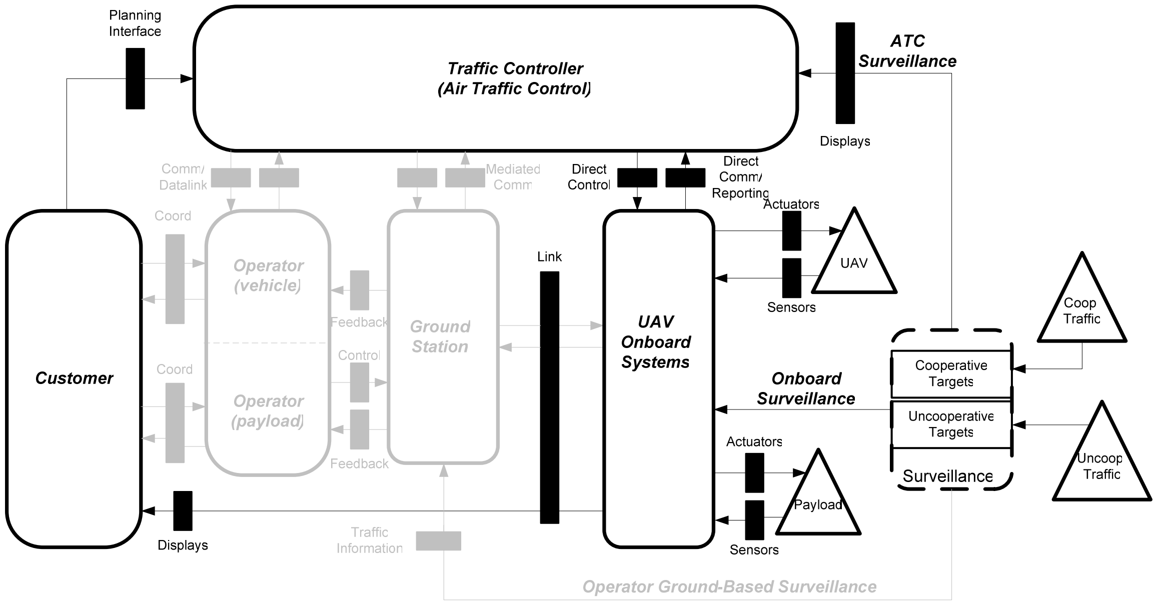

Figure 11: Autonomous & Adaptive UAV Concept

From the previous examples, there is a broad range of potential architectures for UAV operation that can provide traffic avoidance capabilities and vehicle control. Current UAV systems have yet to demonstrate the ability to autonomously adapt to changes in the environment and respond to air traffic control commands. This is likely due to the current lack of capability for air traffic to give commands in a form that can be utilized directly by aircraft automation, such as datalink. Compliance with the current voice communicated commands is also problematic as speech recognition is still prone to errors. Fully autonomous operation is also limited by the ability of current autonomy methods to adapt to unplanned situations and assure safe flight without human intervention or supervision.

3.3 UAV Performance Capabilities

In considering future UAV operations in the NAS, it is important to recognize that the label "Unmanned Aerial Vehicle" can be applied to vehicles with a broad range of configurations, sizes, and performance capabilities. A general classification nomenclature representative of common sizes and performance capabilities is useful in discussion of safety implications. This section will examine the performance of current UAVs, determine where natural classification boundaries exist, and discuss the safety implications of the performance capabilities of each class.

3.3.1 Potential Classifications

When referring to UAV classes, there is a mix of nomenclature used from a variety of sources, including the military, research community, manufacturers, and professional organizations. The various nomenclatures are based on a variety of parameters including mass, vehicle configuration, designed application, level of autonomy, type of operation, or military level employment. There is currently a lack of consensus for classification of civil UAVs, although both the UK and Australia have developed classifications between "small" and "large" UAVs based on mass [26,27].

Current manned aircraft certification classes are primarily differentiated by mass as light or heavy[1], and by aircraft configurations such as rotary or fixed-wing. Further differentiations are made by type of operation, number of passengers carried, and by the type and number of engines. In UAV systems, the parameters most relevant to risk to the general public are the mass and size of the vehicle, its kinetic energy or momentum, and the operational capabilities of the aircraft. To maintain uniformity with current manned regulation, UAV classifications were considered with mass as a primary discriminator. Performance capabilities were analyzed with respect to mass to determine if natural breakpoints in performance were present that allowed the classifications to be representative of common operating characteristics. This analysis of current UAV performance was limited to fixed-wing aircraft. Rotary-wing UAVs are primarily designed for operation close to the ground, therefore mass is the most likely discriminator of that class of aircraft.

Five categories of current UAVs were defined for this analysis from a combination of research and military literature. The categories are Micro, Mini, Tactical, Medium Altitude, and High Altitude. Medium and High altitude UAVs are also known

[1] Certification of light aircraft is governed by FAR Part 23 and are less than 12,500 lb. Certification of heavy aircraft is governed by FAR Part 25, and is greater than 12,500 lb. They are often referred to as Part 23 or Part 25 aircraft.

as Medium Altitude Long Endurance (MALE) or High Altitude Long Endurance (HALE) UAVs, indicating their ability to stay aloft for long periods of time. It is also possible that an additional category representing a heavy cargo-class UAV will emerge. Because current production examples do not exist, this type was not included in the performance analysis. Examples of the UAV mass spectrum are shown in Figure 12, along with potential classification boundaries.

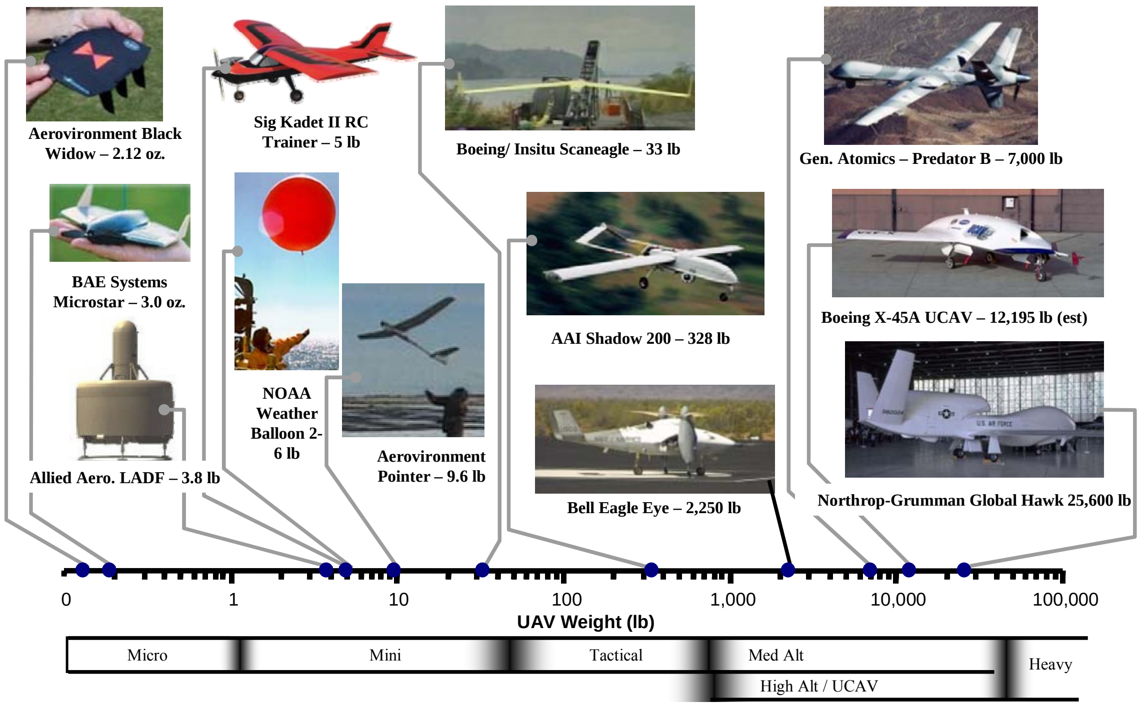

Figure 12: Mass Spectrum of Current UAVs

3.3.2 Performance Analysis

The performance data for several current UAVs were gathered from UAV reference literature [40] and UAV manufacturer reports. Mass, ceiling, maximum endurance, and cruise speed data were assembled for several fixed-wing UAVs that are currently in production, operational service, or utilized for research. A summary of the data is included in Appendix A for reference.

The maximum operating altitude of several current UAVs, is shown in Figure 13, along with the boundaries for different classes of controlled airspace. Micro, Mini, and Tactical UAVs show clear breakpoints in mass and maximum altitude. Micro & Mini UAVs are likely to be operated close to the ground and are generally not capable of reaching above 5,000 ft. Tactical UAVs occupy a much broader mass range, from 30 to

1,000 lb and are primarily distinguished by their ability to operate higher, approaching the boundary of Class A airspace at 18,000 ft. The *Seascan* UAV is a notable outlier in the mini category, with a ceiling of 18,000 ft. However, it is generally operated similar to other Mini UAVs.

The distinction between Medium and High Altitude UAVs is primarily in their operating altitude, but not in vehicle mass. Medium altitude UAVs are typically operated around the region of Class A airspace, while several high alttitude UAVs have the capability to be operated above FL 600 into uncontrolled airspace. For operations in the NAS, high altitude aircraft must pass through the same operating range as medium altitude aircraft in transit to their operating altitude. Therefore, they may not present different safety considerations than medium altitude aircraft.

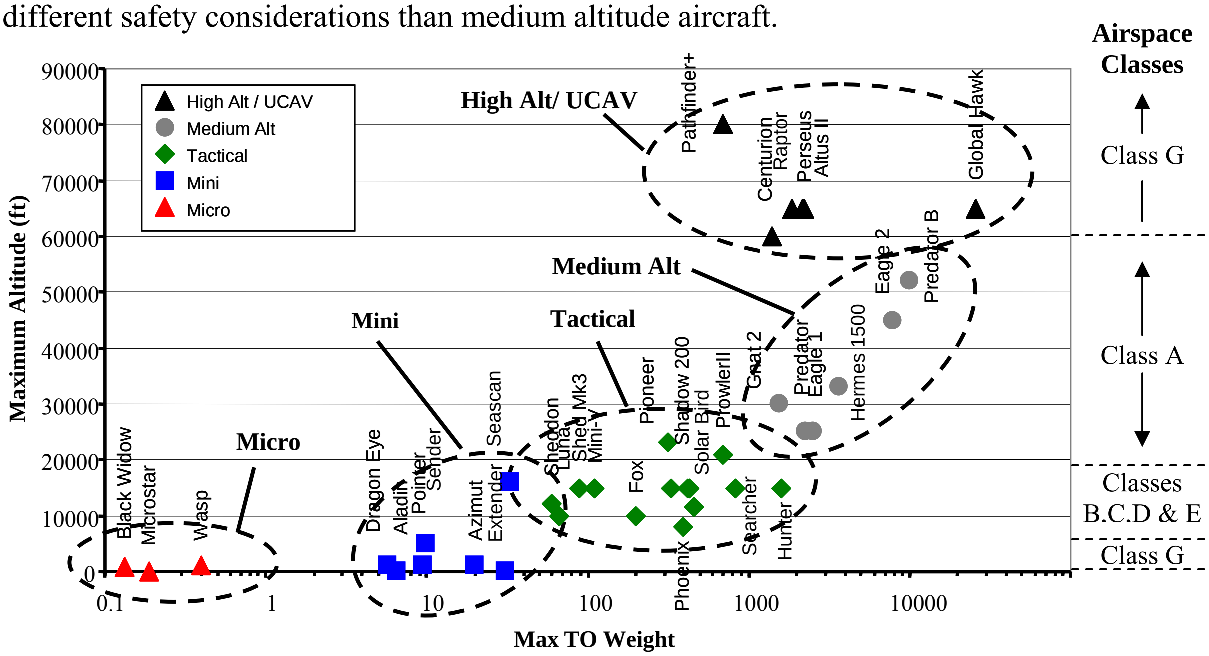

Figure 13: Maximum Altitude of Current UAVs

The maximum endurance of several UAVs is shown in Figure 14. Micro UAVs typically have endurances measured in minutes, as they typically carry enough power to remain aloft for long periods of time. As the mass of UAVs increase, the current maximum endurance capability also increases exponentially. Mini UAVs can typically be operated for several hours, Tactical on the range of 5-10 hours, and Medium and High altitude from 10 hours to days.

High endurance UAVs may remain in the NAS for over 24 hours, during several personnel changes both on the ground and in the NAS. Several concepts have been proposed to extend endurance to days or weeks, with UAVs acting as high altitude pseudo-satellites, flown above the majority of air traffic. For long endurance missions, component reliability may become a critical factor in the ability to complete the UAV's mission. There also may be more instances of failure due to the longer operation and complexity of shift changes.

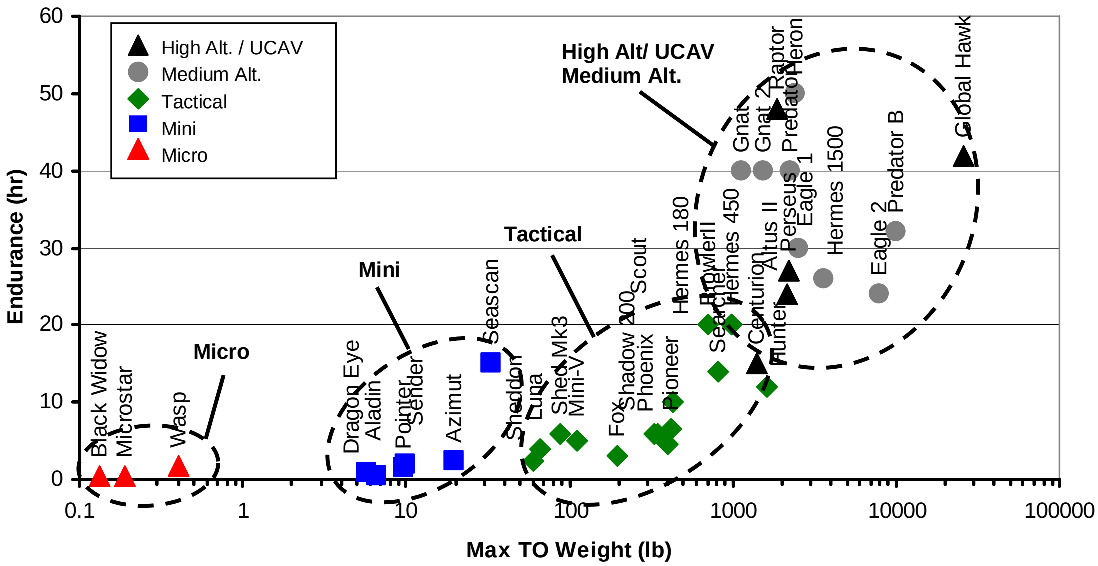

Figure 14: Maximum Endurance of Current UAVs

Integration of UAVs can be problematic if the UAV's performance envelope is significantly different from other aircraft. Figure 14 shows the speed-altitude envelope for several UAVs. As the reader may note, most mini, tactical, and rotary UAVs lie on a line of increasing speed with increasing altitude. Mini UAVs typically have a maximum speed from 30-90 knots, and tactical from 80-110 kts. At these altitudes, UAVs can achieve the same speed as several other general aviation aircraft. However, if the UAV is loitering at a different speed, it will change the potential collision scenarios. More collisions would be likely to occur where another aircraft is overtaking the UAV, which may be especially difficult for forward or side-looking sensors to prevent.

The characteristics of medium altitude and high altitude class of vehicles could be problematic. Medium altitude aircraft exhibit a wide range of maximum speed capabilities from 100 to 200 kts. High altitude aircraft have dramatically different maximum speeds. They range from 20 kts for the solar/electric-powered *Helios* to 400 kts for the jet-powered *Global Hawk*. Slower speeds in the High Altitude class would be likely to require special consideration by air traffic control to separate from other aircraft during their flight.

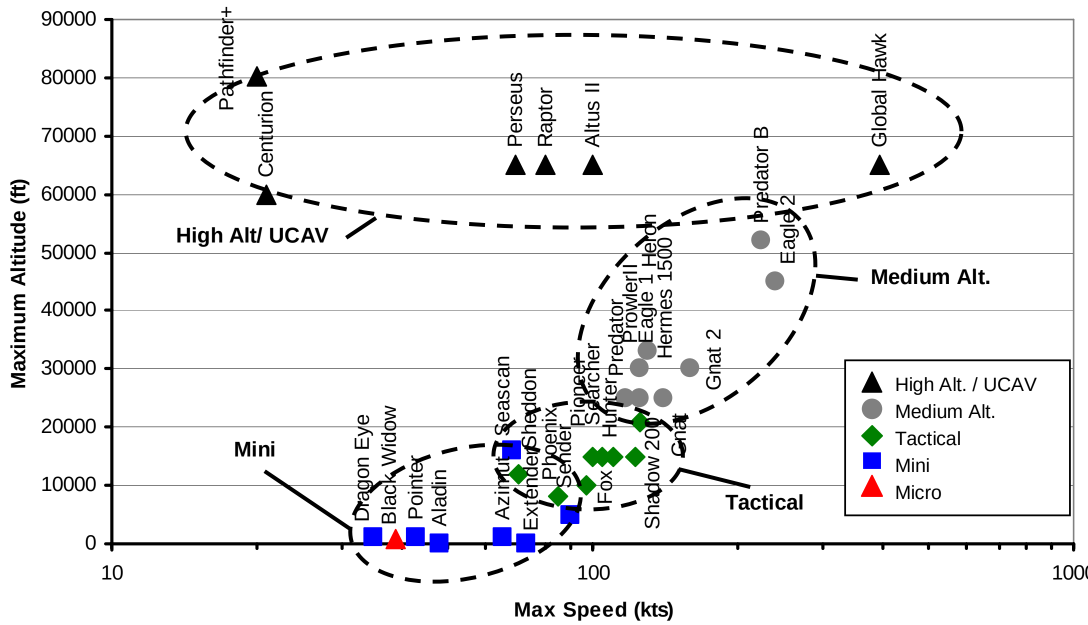

Figure 15: Speed vs. Altitude of Current UAVs

3.4 Representative Aircraft for Classification

The Micro, Mini, Tactical, MALE, and HALE classifications of current UAVs capture common size and operating characteristics. These classifications, representative examples, mass and operating ranges are summarized in Table 6. To represent the possibility for air transport-sized cargo UAV operations, a Heavy class of aircraft was also added. The representative aircraft used for analysis from top to bottom are: the Aerovironment *Black Widow*, the Aerovironment *Pointer*, the AAI *Shadow 200*, the General Atomics *Predator A*, the Northrop-Grumman *Global Hawk*, and the McDonnell-Douglas MD-11. The UAVs and their characteristics will be used as representative examples for the analysis of the ground impact hazard in Chapter 6.

Table 6: Summary of Vehicle Classes

<table>
<tr><th>Class</th><th>Representative Aircraft</th><th>Mass Range</th><th>Operating Area</th><th>Operating Altitudes</th></tr>
<tr><td>Micro</td><td></td><td>Less than 2 lb</td><td>Local</td><td>Near-surface to 500 ft</td></tr>
<tr><td>Mini</td><td></td><td>2 to 30 lb</td><td>Local</td><td>100 to 10,000 ft</td></tr>
<tr><td>Tactical</td><td></td><td>30 to 1,000 lb</td><td>Regional</td><td>1,500 to 18,000 ft</td></tr>
<tr><td>MALE</td><td></td><td rowspan="2">1,000 to 30,000 lb</td><td>Regional/ National</td><td>18,000 ft to FL 600</td></tr>
<tr><td>HALE</td><td></td><td>Regional/ National / International</td><td>Above FL 600</td></tr>
<tr><td>Heavy*</td><td></td><td>Over 30,000 lb</td><td>National / International</td><td>18,0000 ft to FL 450</td></tr>
</table>

Chapter 4

Regulatory Bases for Civil Operation of Unmanned Aircraft

Congress created the Federal Aviation Administration (FAA) and gave it the authority and responsibility to regulate the air transportation system. While the FAA has taken steps to ensure the safety of UAV operations, they have not generally defined an unmanned aerial vehicle as a type of aircraft or created specific regulatory procedures for all types of UAVs. Current FAA rules and regulations applicable to unmanned aircraft are of limited scope. Rules have been established governing model aircraft, and current regulations apply to the operation of unmanned balloons, kites, and rockets. Additional UAV operations are approved through the Certificate of Authorization process introduced earlier. The myriad of rules governing unmanned aircraft has created uncertainty for some members of the UAV community regarding the extent to which different UAV types may fall under the jurisdiction of the FAA. There has also been confusion in the model aircraft community regarding an FAA decision that model aircraft used for commercial purposes are not governed by currently established model aircraft rules [41].

The first half of this chapter outlines the statutory basis for the FAA's authority and safety mandate and how it applies to UAVs. The second half details the current rules and regulations governing the operation of unmanned aircraft. The investigation shows that UAVs fit the general definition of *aircraft*, but there are precedents for defining other aircraft, such as ultralights, as *vehicles*. Regardless of classification as vehicles or aircraft, regulation of UAVs is consistent with the authority and mandate of the FAA, and that there is a legal basis for distinguishing between commercial and recreational operations. Under the FAA's authority, there are a variety of policy mechanisms that can be used to ensure safety of UAV operations in the NAS.

4.1 Legal Basis for FAA Regulation of Aircraft

The FAA's mandate to regulate aviation safety is established by Congress and present in federal law. The part of federal law applicable to the FAA's authority is Title 49 of the United States Code (referred to as 49 U.S.C.), which governs transportation. Subtitle I of Title 49 governs the Department of Transportation in which the FAA resides, and Subtitle VII governs aviation programs. The code is amended by congress through reauthorization bills, which establish the budget levels and amend policy priorities of the FAA as necessary.

Federal law states that the Secretary of Transportation, "shall consider … assigning and maintaining safety as the highest priority in air commerce" [1] The code gives the same charge to the administrator of the FAA, with the added task of "enhancing safety."[2] In a separate section describing the duties of the FAA Administrator, federal law states that he or she "shall carry out the duties and powers of the Secretary of Transportation… related to aviation safety[.]"[3]

It is important to note that the main clause in federal law giving responsibility for safety specifically charges the FAA to maintain safety *in air commerce*, not merely in aviation. Air commerce is defined in federal law as

> foreign air commerce, interstate air commerce, the transportation of mail by aircraft, the operation of aircraft within the limits of a Federal airway, or the operation of aircraft that directly affects, or may endanger safety in, foreign or interstate air commerce.[4]

Within the definitions of foreign and interstate air commerce, air commerce is further defined as

> the transportation of passengers or property by aircraft for compensation, the transportation of mail by aircraft, or the operation of aircraft in furthering a business or vocation.[5]

The air commerce clause forms a basis for FAA regulation of recreational aircraft and aircraft involved in air commerce at different safety levels. A distinction is also made between air commerce and air transportation, where air transportation involves

[1] 49 U.S.C. §40101 (a) (1)
[2] 49 U.S.C. §40101 (d) (1)
[3] 49 U.S.C. §106 (g) (1) (A)
[4] 49 U.S.C. §40102 (a) (3)
[5] 49 U.S.C. §40102 (a) (22), 49 U.S.C. §40102 (a) (24)

using the aircraft as a *common carrier* of passengers. The FAA administrator is given the mandate to "classify a regulation or standard appropriate to the differences between air transportation and other air commerce."[1]

There is uncertainty regarding the classification of UAVs as aircraft. Federal law defines an aircraft as "any contrivance invented, used, or designed to navigate, or fly in, the air."[2] Broad interpretation of the definition would include UAVs, but could also include paper airplanes. Further understanding can be gained by looking at previous FAA rulemaking. When crafting ultralight regulations, the FAA refers to ultralights as vehicles, not aircraft. In the original preamble of ultralight regulations, ultralights were differentiated from other *aircraft* for purposes of airworthiness and registration. The current language in regulations has been modified, but the distinction between ultralight *vehicles* and other *aircraft* remains. Part 91, the general operating and flight rules do not apply to ultralight aircraft, which are governed by specific flight rules in Part 103 of the Federal Aviation Regulations. Model aircraft, on the other hand, are specifically referred to as aircraft in the advisory circular providing guidelines for their operation [38]. Nonetheless, model aircraft are not specifically mentioned in *regulation*, therefore they have not formally been defined as aircraft

The distinction between vehicles and aircraft is still unclear as it applies to several classes of UAVs. Demonstrated by previous rulemaking, the broad legal definition of aircraft gives the FAA the authority to further define the term. Therefore, UAVs still fall under the responsibility of the FAA, but specific rules may vary depending upon the FAA's classification of certain UAVs as vehicles or aircraft. While the safety mandate for the FAA is specific to air commerce, the FAA's authority over all aircraft operated in federal airspace is reinforced by federal law that makes it illegal for a person to operate an aircraft, unless authorized by the FAA or with limited exceptions[3], without being registered with the FAA.[4] Violation of this law carries potential civil penalties also included in the federal code. Therefore, it is illegal to operate a UAV apart from existing rules if not approved by the FAA.

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[1] U.S.C. §44701 (d) (2)
[2] U.S.C. §40102 (a) (6)
[3] Exceptions to registration requirements are granted mainly for military or foreign aircraft operations, and for a reasonable period of time after the transfer of ownership of an aircraft
[4] U.S.C. §40101 (a)

Federal law did not anticipate the operation of unmanned aircraft that present harms to the public on the ground, but not to the traveling public. There is no specific legal mandate for the FAA to protect the public on the ground from harm caused by aviation. In practice, FAA regulations are crafted to protect both the general public, and all participants in aviation. Language in federal law is consistent with a general responsibility for aviation safety. Therefore the FAA should continue to ensure the safety of the public on the ground due to UAVs.

4.2 Mechanisms for Safety Regulation

The FAA exercises authority over aviation through the Federal Aviation Regulations (FARs), or Title 14 of the Code of Federal Regulations. The components of the air transportation system over which the FAA has authority are described by 49 U.S.C. Chapter 447. The chapter does not contain language that would differentiate between manned and unmanned operation. By federal law, the FAA has the authority to regulate the manufacture and maintenance of civil aircraft, individual and corporate operators of aircraft, liability for aircraft accidents, ground infrastructure required for air commerce, and the operation and equipage of aircraft operated in controlled airspace. The two mechanisms that are of primary importance in this safe study of UAVs are airworthiness requirements.

When a manufacturer obtains a type certification from the FAA, the FAA certifies that that aircraft is airworthy to the standard defined by the regulations. Airworthiness means that the aircraft is safe to fly, controllable, can withstand anticipated flight loads, and can operate safely over its design life. Airworthiness standards are set for design of general classes of aircraft in the Federal Aviation Regulations[1]. Airworthiness is further preserved by standards in maintenance and inspection, ensuring that the aircraft is remains at a designated level of airworthiness during its operation.

The FAA also maintains safety by regulating procedures and standards for operations in the NAS[2]. Operating rules govern the separation of aircraft, responsibilities

[1] FAR Parts 23, 25, 27, 29, 31, 33, and 35

[2] General Operating and flight rules are contained in FAR Part 91, with separate operating rules for specific classes of aircraft in Parts 101, 103, and 105. Additional certification and operational rules govern air carriers and operations for hire in Subchapter G of the FARs.

of the pilot for navigation and control of the aircraft, and procedures for operating in different airspace environments. The operating rules also recognize different levels of control over safety for different aircraft and operational areas of the NAS. Several operating requirements in the federal aviation regulations directly require pilots to operate aircraft safely. Provisions require the pilot to maintain vigilance to see and avoid other aircraft[1], and preclude the operation of aircraft in a reckless manner that endangers another person's life or property[2].

4.3 Current Unmanned Aircraft Rules

Several types of UAVs are currently operated in the NAS, enabled by a variety of regulatory mechanisms. Unmanned kites, rockets, and balloons are governed by specific FARs, while model aircraft are operated under advisory circular guidelines and an established private regulatory mechanism. Other UAV operations must be approved by certificate authorizing an exemption to the regulations. The three types of operations are examined in the context of different mechanisms for enforcing safety, and different control architectures applied to current UAV operations.

4.3.1 Model Aircraft

Model aircraft, also called radio-controlled (RC) aircraft, are typically flown by hobbyists within line of sight. They may be helicopters or fixed wing aircraft, and also may utilize a variety of propulsion types. The system has evolved such that model aircraft are separated from other users of the NAS, and are controlled by private guidelines and insurance mechanisms through the Academy of Model Aeronautics (AMA).

The FAA publishes Advisory Circular 91-57 [37], which establishes voluntary guidelines for the operation of model aircraft. The advisory circular states that the aircraft should be operated at an altitude less than 400 ft, away from populated areas, and not within 3 miles of an airport without notifying the airport operator. It also states that model aircraft should give the right of way to and avoid flying in the vicinity of full scale aircraft. The Academy of Model Aeronautics (AMA) publishes a safety code [42] which

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[1] FAR § 91.113

[2] FAR § 91.13, § 103.9, § 101.7

is enforced at AMA airfields and which must be followed for the AMA's liability insurance to apply. The safety code specifically incorporates the provisions in AC 91-57, and additionally requires that the aircraft be less than 55 lbs, or follow additional procedures for approval.

To ensure the safety of model aircraft operations, there has been an evolved responsibility by a private organization for enforcing safety practices, based on federal guidelines. This approach has limits. Membership in the organization is voluntary, and compliance with both FAA procedures and AMA guidelines is also strictly voluntary. Therefore, there is limited ability to enforce safe model aircraft practices. Furthermore, recent technological advances are made model aircraft potentially less benign. Recent technological changes have allowed small aircraft to be operated autonomously and beyond line of sight. These technological advancements have also made model aircraft attractive camera platforms for limited commercial use. The FAA has established that commercial operation of model aircraft is in violation of the recreational intentions of AC 91-57 [41].

The AMA has recently taken steps to differentiate itself from the broader UAV community and maintain its authority over recreational, non-commercial flight of model aircraft. Consistent with this distinction, the 2004 AMA safety regulations were changed to preclude autonomous and commercial operation [43]:

> A model aircraft is defined as a non-human-carrying device capable of sustained flight in the atmosphere not exceeding the limitations established in this Code, exclusively for recreation, sport, and/or competition activities. The operators of radio control model aircraft shall control the aircraft from the ground and maintain unenhanced visual contact with the aircraft throughout the entire flight operation. No aircraft shall be equipped with devices that would allow for autonomous flight.

The language of the 2005 safety code maintained the distinction between recreational and commercial operation. The provision regarding autonomous flight was reworded to preclude devises that allow operation beyond the line of sight [42]:

> The operator of a radio-controlled model aircraft shall control it during the entire flight, maintaining visual contact without enhancement other than by corrective lenses that are prescribed for the pilot. No model aircraft shall be equipped with devices which allow it to be flown to a selected location which is beyond the visual range of the pilot.

For model aircraft, the safe operation rests on the assumption that the aircraft will be kept small and will be operated under positive control, within line of sight. The enforcement of control is through an established set of practices within the recreational aircraft community. The AMA ensures safety through a published safety code and enforcement through insurance protection from liability.

The enforcement of safety is limited by membership to the organization or community. Therefore, operations of model aircraft still pose a risk to the public on the ground and other users of the airspace. As will be further discussed in Chapter 5, there has been several near midair collisions between model aircraft and manned aircraft reported in the Aviation Safety Reporting System. There are also cases where operators or bystanders have been fatally wounded by an out of control model aircraft [44].

4.3.2 Moored Balloons, Kites, Unmanned Rockets, and Unmanned Free Balloons

FAR Part 101 governs the operation of Moored Balloons, Kites, Unmanned Rockets, and Unmanned Free Balloons. Subpart (a) contains general requirements, while Subpart (b) governs unmanned balloons and kites, (c) unmanned rockets, and (d) unmanned free balloons. The regulation proscribes several mechanisms for mitigating the risk posed by three categories of objects to other users of the NAS and persons and property on the ground. Operations of the objects do not require positive control by the operator or launcher of the balloon, kite, or rocket beyond the initial release. Therefore, the mitigation measures required are passive in nature, and the part does not contain analogous “flight rules” to unmanned aircraft.

While each subpart contains specific exemptions, operation restrictions, and FAA notification requirements for each type of vehicle, there are common methods of risk control both to persons and property on the ground and other aircraft through weight and operating restrictions, and notification and visibility requirements. Subpart (a) of Part 101 also generally states that “no person may operate any moored balloon, kite, unmanned rocket, or unmanned free balloon in a manner that creates a hazard to other persons, or their property.” It also states that they may not allow an object to be dropped from the kite, rocket, or balloon that endangers persons or property.

Several exemptions from Part 101 are made for small-mass, or low-altitude operations. These exemptions allow unregulated use of moored balloons, free balloons, and model rockets as long as the criteria for exemption are met. Requirements for exemption vary, but thresholds are set based on a combination of size, mass, material construction, density, or operating characteristics the object. For example, unmanned rockets are exempt if they weigh less than 16 oz. and are constructed of paper, wood, or breakable plastic, and utilize a form of propellant dictated by the regulations. Moored balloons are exempt if they are less than 6 ft in diameter, and have a gas capacity of less than 115 ft^3. Unmanned free balloons must meet several criteria to be exempt for the regulations: one of which is the requirement that the weight per surface area of any side of the payload may not exceed 3 oz/in^2. The size, density, and material limitations reduce the risk of collision the objects pose to other aircraft or the general public.

The three subparts of Part 101 also contain provisions to restrict operation from high-density areas, both around airports and in populated areas, reducing the risk posed to the general public and other aircraft. Moored balloons and unmanned rockets governed by Part 101 are prohibited from operating within 5 miles of an airport. Unmanned free balloons may not be operated under 2,000 ft in airspace Classes B, C, D, or E designated for an airport. With respect to protection of persons and property on the ground, unmanned rockets governed by Part 101 are not allowed to be operated within 1,500 ft of any person who is not involved in the operation, and free balloons are prohibited from operating within its first 100 feet of ascent in the vicinity of a “congested city or town,” and must not endanger persons or property when it returns to the surface.

Further restrictions are placed on operation to mitigate potential collisions with manned aircraft through visibility requirements. Objects governed by Part 101 are restricted from launch in meteorological conditions where they would not be visible to other aircraft. Both moored and free balloons generally require high visibility pennants or streamers to be attached to any line at 50 ft intervals. Unmanned rockets cannot be operated at night, but balloons may be operated at night if they have visible lights on the balloon, payload, and attached lines. Free balloons are also required to be visible to ground radar. The operator is also required to make regular position reports of the balloon to the local Air Traffic Control facility unless the requirement is waived.

Notification is also used to control the risk to other aircraft by unmanned and uncontrolled operations. Although details vary, when required the operators generally must notify the FAA regional office or air traffic control of the proposed operation 6 to 24 hours in advance Notification is required for moored balloons and kites above 150 ft and unmanned rockets and balloons governed by Part 101. Notification are usually published as notice to airmen or provided by air traffic control to traffic in the area to alert them to the potential of the other objects in the airspace.

Safety for the kites, balloons, and rockets that are operated under Part 101 is achieved a combination of factors. Ambient levels of risk are reduced by separating operations from high density areas. The potential for midair collisions is reduced through visibility requirements or notification to air traffic control. The visibility requirements for balloons and kites are in place so piloted aircraft can avoid the objects, without requiring the objects to avoid manned aircraft. Should a collision occur, the magnitude of potential harm is reduced by limitations on the size, density, and construction of the objects.

4.3.3 Certificate of Authorization

All UAV flights within the NAS not operated as model aircraft or under FAR Part 101 must be approved under a certificate of authorization (COA) from the FAA, authorizing an exception to the current regulations. The UAV COA guidelines were initially formulated for military UAV flights within the NAS, and are contained in FAA Order 7610.4 – Special Military Operations [28]. The military standards have since been applied to civil UAV operations as well. From the order, the application for the COA must be made to the regional FAA office where the flights will take place, and must include the following elements:

1. Detailed description of the intended flight operation including the classification of the airspace to be utilized.
2. ROA physical characteristics.
3. Flight performance characteristics.
4. Method of pilotage and proposed method to avoid other traffic.
5. Coordination procedures.
6. Communications procedures
7. Route and altitude procedures.
8. Lost link/mission abort procedures.
9. A statement from the DOD [or commercial] proponent that the ROA is airworthy.

The COA process is used to approve an exception to current regulations. Therefore, it requires lengthy lead time for approval and extensive planning prior to a UAV mission. As an exception process, it also forces a very conservative approach to ensuring safety, often limiting the area of operation and requiring adherence to a pre-determined flight path. The provisions of the COA allow the approving authority to ensure both the airworthiness of the UAV and to define procedures for operating the UAV. By a review instead of regulation process, the same mechanisms for safety that are enforced for manned aircraft are also enforced for UAVs.

Each UAV COA must be reviewed by regional FAA authorities, resulting in different standards depending upon the approving authority. Additional differences in procedures are introduced between civil and military UAV operations, which are also approved through separate FAA departments. The process is inefficient, and does not result in clear standards for users to follow in designing UAV applications.

4.4 Conclusions

From federal law, it is clear that the FAA has the responsibility and authority for ensuring the safe operation of UAVs in the NAS. There are also several mechanisms currently used to ensure the safety of unmanned aircraft depending upon the nature of risk posed by the operations, and the type of system. The currently established rules governing UAV operations are limited in scope. If routine operations are to be achieved, it is necessary to counter the inefficiency of the detailed COA process by crafting new UAV regulations based on FAA system safety standards. The methodology for assessing risk according FAA system safety guidelines is presented in the next chapter. The safety analysis examines the risk to the general public on the ground and in other aircraft posed by different UAV operation to inform future UAV rulemaking.

Chapter 5

System Safety Analysis

The use of UAVs, like other aviation technologies, poses a potential harm to the general public. This potential harm is measured by the metric of *risk*, which is defined as both the "*likelihood* of an accident, and the *severity* of the potential consequences." [45] As discussed in Chapter 4, it is the responsibility of the Federal Aviation Administration to ensure the safety of UAV operations in the NAS. FAA Order 8040.4 [46] specifies that a risk management process should be applied to all high-consequence decisions by the FAA, which includes the incorporation of a new class of aircraft in the NAS. Published in support of Order 8040.4, the FAA System Safety Handbook (SSH) [47] provides general guidance to FAA personnel and contractors on implementing a risk management process but does not supersede existing regulations. Other system safety regulations include advisory circulars for systems in Part 23 and 25 aircraft [48,49].

FAA system safety policies were used as guidance to investigate the safety considerations for operation of UAVs in the NAS. The purpose of this chapter is to outline the methodology used in the system safety analysis. The methodology includes both the identification of adverse effects and determination of the risk of each of the effects. In addition, the regulatory requirements on target levels of safety were also compared to current levels of safety for the two critical hazards identified: ground impact and midair collision.

5.1 Risk Assessment Methodology

To determine the safety implications of potential UAV operations, a risk assessment methodology was used. The first step of a risk assessment is to identify the hazards due to the operation of a system, which are situations that present the potential for an accident. Next, the likelihood of occurrence of each hazard is estimated. The risk of a given hazard is defined as the combination of the severity of the hazard and its likelihood of occurrence. This approach is outlined in Chapter 7 of the system safety handbook, as the process for system hazard identification and risk assessment [47]:

- Hypothesize the [operational] scenario.
- Identify the associated hazards.
- Estimate the credible worst case harm that can occur.
- Estimate the likelihood of the hypothesized scenario occurring at the level of harm (severity).

The tradeoff in risk management is between the rate of occurrence of adverse events and their associated consequences. This tradeoff is represented by the cause-consequence matrix shown in Table 7. The matrix categorizes risk based on four levels of occurrence and five levels of potential severity. Severity and likelihood definitions will be further discussed in the next section.

Table 7: Cause-Consequence Relationship in Risk Management

Severity/ Likelihood	No Safety Effect	Minor	Major	Hazardous	Catastrophic
Probable					
Remote					
Extremely Remote					
Extremely Improbable					

High Risk
Medium Risk
Low Risk

Hazard identification and risk assessment is typically performed when a full description of the system exists. To compare risk across the broad range of potential UAV systems operated in the NAS, there is a need to maintain general applicability in the risk assessment process. To accomplish this, a consequence-based approach to the identification of hazards was taken. This approach focuses the risk assessment on the most severe harms due to UAV operations. The harms are selected and analyzed, encompassing the many specific failures that may result in the harm. From comparison to manned aircraft reliability requirements, events with the most severe consequences are typically the critical design drivers of the system, and this allows a preliminary analysis to capture the critical harms relevant to UAV operation. The risk assessment process quantifies the risk of the critical hazards and determines what level of control or mitigation is required.

5.1.1 Severity Classifications

The FAA defines five classes of severity of consequences in the SSH, ranging from "catastrophic" to "no safety effect." The explanations of effects that fall under each level of severity are included in Table 8. The severity definitions included the SSH are consistent with the advisory material for system safety of Part 23 [48] and Part 25 [49] aircraft. Part 25 does not include the subcategory of hazardous events.

Table 8: FAA System Safety Handbook Severity Definitions [47]

Severity Level	Definition
Catastrophic	Results in multiple fatalities and/or loss of the system
Hazardous	Reduces the capability of the system or the operator ability to cope with adverse conditions to the extent that there would be: - Large reduction in safety margin or functional capability - Crew physical distress/excessive workload such that operators cannot be relied upon to perform required tasks accurately or completely Serious or fatal injury to small number of occupants of aircraft (except operators) Fatal injury to ground personnel and/or general public
Major	Reduces the capability of the system or the operators to cope with adverse operating condition to the extent that there would be - Significant reduction in safety margin or functional capability - Significant increase in operator workload - Conditions impairing operator efficiency or creating significant discomfort - Physical distress to occupants of aircraft (except operator) including injuries - Major occupational illness and/or major environmental damage, and/or major property damage
Minor	Does not significantly reduce system safety. Actions required by operators are well within their capabilities. Includes: - Slight reduction in safety margin or functional capabilities - Slight increase in workload such as routine flight plan changes - Some physical discomfort to occupants or aircraft (except operators) - Minor occupational illness and/or minor environmental damage, and/or minor property damage
No Safety Effect	Has no effect on safety

One of the fundamental differences in the safety process of UAVs compared to manned aircraft is apparent in Table 8. The severity definitions related to occupants of the aircraft do not apply to an unmanned system. In UAV operation, the most severe possible outcomes are those that result in injury to the general public, either in other aircraft or on the ground. Although a catastrophic event is defined as resulting in multiple fatalities and/or the loss of the entire system, it is likely that the loss of system criterion will not be applied to UAVs. The destruction of a UAV system does not immediately constitute a safety risk and is therefore not inherently catastrophic.

The two most severe consequences of UAV operation are catastrophic events, which are events that result in multiple fatalities, and hazardous events, which result in a small number of fatalities. Property or environmental damage are potential effects of UAV accidents and would be labeled as major. Consistent with examining the critical hazards, events with a category of major and below were not included in this risk analysis.

There are two major types of events that result in harm to the public. Ground impact can endanger the general public, and midair collision with a manned aircraft can threaten the safety of the passengers aboard that aircraft. Both effects are critical system design drivers that have implications for UAV operations and reliability requirement. Therefore, the two events were further analyzed as the two critical harms in UAV operation. When analyzing ground impact, it is assumed that the event would not result in a large number of fatalities, and would therefore be classified as hazardous and not catastrophic. Midair collision should be considered as a catastrophic event.

There are other harms that are possible due to UAV operation that have not been included in the analysis, one of which is the use of a UAV in a terrorist attack. Terrorism presents a security concern, which must be considered across several modes in the air transportation system. While it is a valid regulatory concern, it is beyond the scope of this safety analysis.

5.1.2 Likelihood of Occurrence

The second component of risk shown in Table 7 is the assignment of the likelihood of occurrence of an event. The likelihood of occurrence of an event is measured as the average probability that an event will occur per hour of operation of the system. When that likelihood of occurrence is used as a design standard in the system, it is also known as the target level of safety (TLS).

Four categories of likelihood are defined by the FAA, ranging from probable to extremely improbable. Each level of likelihood has a qualitative and quantitative definition. The qualitative definitions from the FAA system safety handbook [47] are shown in Table 9. The quantitative levels vary across FAA advisory material depending on the system. Definitions are consistent between the advisory circular for Part 25 aircraft [49] and the system safety handbook [47], except for a lack of a hazardous category in the former. Likelihood definitions vary for different types of Part 23 aircraft in recognition of different realizable equipment reliability levels [46]. A comparison of the likelihood of occurrence definitions across regulatory guidance is shown in Table 10. The broad range of the definition of improbable in AC 25.1309 reflects the lack of a hazardous classification of consequence. Part 23 further divides aircraft into four classes depending upon propulsion type and weight[1]. The most stringent requirements are dictated by the system safety handbook.

Table 9: Qualitative Likelihood of Occurrence Definitions

Likelihood	Definition
Probable	Anticipated to occur one or more times during the entire system/operational life of an item.
Remote	Unlikely to occur to each item during its total life. May occur several times in the life of an entire system or fleet.
Extremely Remote	Not anticipated to occur to each item during its total life. May occur a few times in the life of an entire system or fleet.
Extremely Improbable	So unlikely that it is not anticipated to occur during the entire operational life of an entire system or fleet.

[1] Definitions of AC 23.1309 Aircraft Classes [48]:
I: Typically single reciprocating engine under 6,000 lb
II: Multiple reciprocating engines or single turbine engine under 6,000 lb
III: Single reciprocating and turbine engines, multiple reciprocating and turbine engines under 6,000 lb
IV: Commuter Category

Table 10: Comparison of Likelihood of Occurrence Definitions

<table>
<tr><th colspan="2" rowspan="2">Guidance Source</th><th colspan="8">Likelihood of Occurrence (by order of Magnitude)</th></tr>
<tr><th>10^{-3}</th><th>10^{-4}</th><th>10^{-5}</th><th>10^{-6}</th><th>10^{-7}</th><th>10^{-8}</th><th>10^{-9}</th><th>below</th></tr>
<tr><td colspan="2">FAA SSH</td><td colspan="2">Probable</td><td colspan="2">Remote</td><td colspan="2">Extremely Remote</td><td colspan="2">Extremely Improbable</td></tr>
<tr><td colspan="2">AC 25.1309</td><td colspan="2">Probable</td><td colspan="4">Improbable</td><td colspan="2">Extremely Improbable</td></tr>
<tr><td rowspan="4">AC 23.1309</td><td>Class[1] IV</td><td colspan="2">Probable</td><td colspan="2">Remote</td><td colspan="2">Extremely Remote</td><td colspan="2">Extremely Improbable</td></tr>
<tr><td>III</td><td colspan="2">Probable</td><td colspan="2">Remote</td><td>Extremely Remote</td><td colspan="3">Extremely Improbable</td></tr>
<tr><td>II</td><td colspan="2">Probable</td><td>Remote</td><td>Extremely Remote</td><td colspan="4">Extremely Improbable</td></tr>
<tr><td>I</td><td>Probable</td><td>Remote</td><td>Extremely Remote</td><td colspan="5">Extremely Improbable</td></tr>
</table>

5.2 Empirical Levels of Risk

In comparison to regulatory guidance, empirical accident data are informative of the actual level of risk present in aviation. The purpose of this section is to investigate the rate of occurrence of ground fatalities and midair collisions in the United States to illustrate the current level of risk in the system. In some cases, the level of risk experienced differs significantly from the guidelines proposed in system certification.

5.2.1 Ground Fatalities

A review of NTSB Accident Data [18] was conducted to determine the current number of ground fatalities due to commercial aviation accidents in the United States. For scheduled and unscheduled air carrier operations, all accidents resulting in fatalities from 1984 to 1999 were reviewed. Based on the accident narrative, ground fatalities from each accident accidents were classified depending on whether the individual was involved or uninvolved in the operation of the aircraft. For example, a ground crew member who is fatally injured after being run over by an aircraft would be classified as an involved fatality. Uninvolved personnel were typically members of the general public who died when an aircraft collided with their vehicle or residence.

The number of uninvolved fatalities represents a risk to members of the general public who do not receive direct benefit from aviation. As shown in Figure 16, the number of uninvolved fatalities in the general public due to scheduled and unscheduled air carrier operations ranges from 0 to 4 annually. This corresponds to a rate on the order of 5×10^{-7} fatalities per hour of operation. The measure is distinct from the fatality risk of passengers per flight hour or departure, which is commonly reported. It demonstrates that current aviation operations impose a risk to the general public on the order of 5 fatalities per hour of operation.

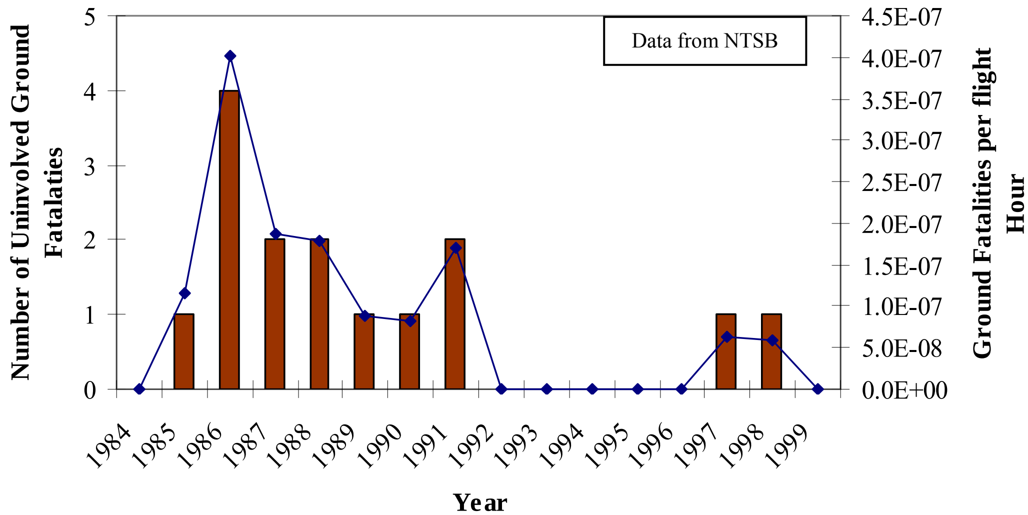


Figure 16: Uninvolved Ground Fatalities Due to Air Carrier Accidents

A similar analysis was performed for general aviation operations. The data source for general aviation aircraft [17] classifies "occupant" and "non-occupant" fatalities. The non-occupant fatalities include fatalities in other aircraft due to midair collisions as well as fatalities on the ground. The data were presented in a form where it was not possible to differentiate whether the fatally injured persons were involved or uninvolved in the operation of the aircraft. Therefore, the non-occupant fatality data presented below are an upper bound on the number of fatalities in the general public per year. From this data, general aviation accidents result in an average of 15 non-occupant fatalities per year, which is on the order of 5 $x10^{-7}$ fatalities per hour of operation.

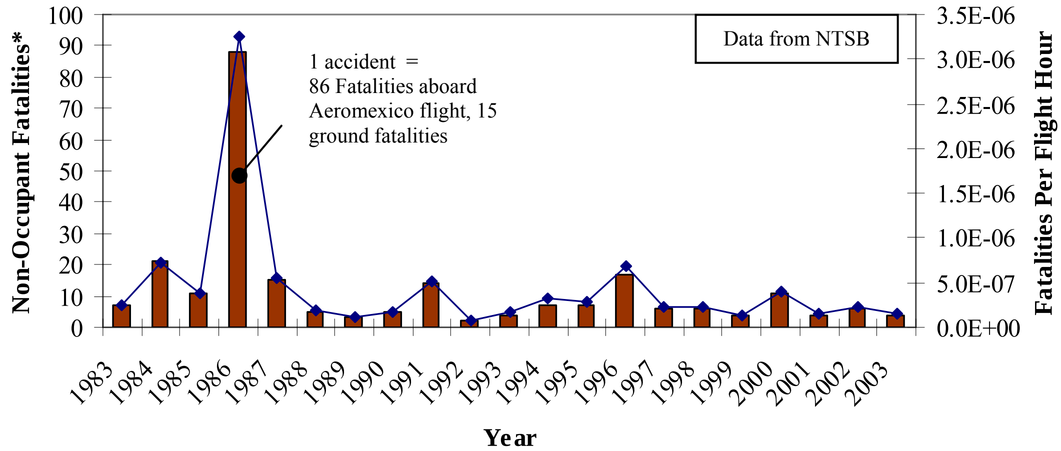


Figure 17: Non-Occupant Fatalities Due to General Aviation Accidents

Both general aviation and commercial aviation operations exhibit similar levels of safety with respect to ground fatalities of 5 x 10^{-7} fatalities per hour of operation. This rate of occurrence is half an order of magnitude above the most stringent required level of safety. In addition, ground fatality risk has been shown by one statistical study to increase by two orders of magnitude in the vicinity of airports [50][1].

There are other risks to the general public from aerial accidents, apart from the actual impact of an aircraft with the ground. Aircraft also pose a risk to the public on the ground through the shedding of "parts" from the aircraft. There are anecdotal accounts in the popular press of "blue ice" falling from aircraft and damaging property [51], although in the author's review, no fatalities have yet occurred. Space launch activities pose a risk through the potential shedding of debris, as well. The most salient example of which is the debris from the space shuttle *Columbia* accident. In a casualty expectation analysis of all recovered *Columbia* debris, the expected number of fatalities calculated was 0.11. However, the probability that any one person would become a casualty was 7.6 x 10^{-5} [52]. The high risk is informative of space agency decisions to de-orbit satellites over the ocean.

[1] The study measured the annual risk to an individual of becoming a fatality due to an airplane accident as 1 x 10^{-6} near the airport, which decreased to 1 x 10^{-8} 4 miles from the airport [50]

5.2.2 Midair Collisions

The last midair collision to occur between two air carrier aircraft over the United States was the collision over the Grand Canyon in 1956 resulting in positive radar separation of aircraft in controlled airspace. Midair collisions occur more frequently in general aviation, or between general aviation and air carrier aircraft. Midair collision rates for general aviation from 1991 to 2002 are shown in Figure 18 [37]. The majority of general aviation midair collisions usually occur in VFR conditions, at low altitude and in the traffic pattern [53]. General aviation has experienced midair collision rates on the order of 5×10^{-7}, with a recent decline to 2×10^{-7} collisions per hour of operation. The collision rate experienced in the system is two orders of magnitude more frequent than the most stringent standards, but exceeds standards for Class I general aviation aircraft. The data could not be decomposed further to determine the risk by general aviation aircraft class.

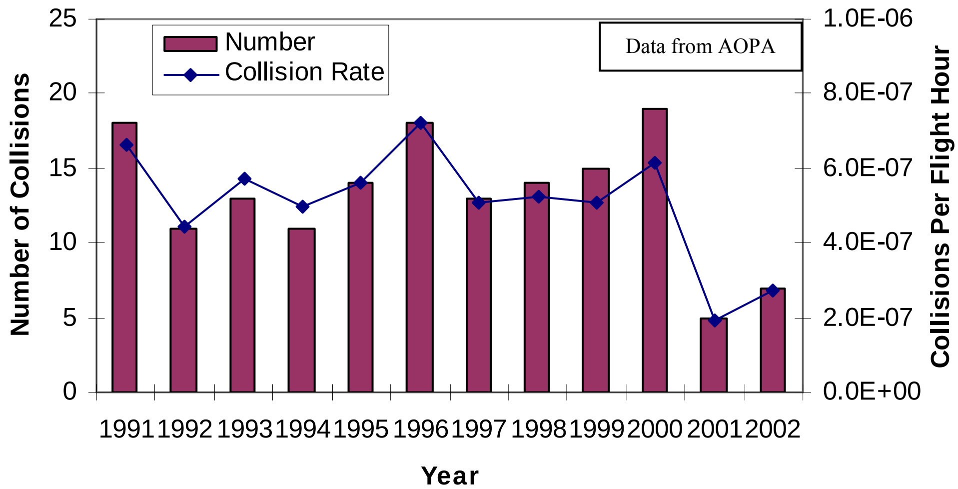


Figure 18: Midair Collisions in General Aviation

Users of the NAS also experience collision hazards from other sources. Bird strikes occur frequently and can cause significant damage to aircraft, although regulations require most aircraft types to withstand bird strikes from birds weighing 2-8 lb[1], and notices to airmen are provided when bird risk is high. Model aircraft, whose operations and regulations were discussed in Chapters 3 and 4, also present a collision hazard to

[1] Requirements differ between Part 23 and Part 25 aircraft, and with which part of the structure must be able to withstand the strike.

manned aircraft. From a review of the Aviation Safety Reporting System (ASRS), there were 10 incidents of near mid-air collisions reported with model aircraft in the traffic pattern around airports from October 1992 to December 2003.

5.3 UAV Risk Analysis Approach

The fundamental approach in risk management is to ensure that hazards in the system are controlled or mitigated to an acceptable level of risk in the system. The goal is to ensure that adverse events with more severe consequences will occur less frequently in the operation of the system, or be eliminated completely. The level of risk of a given event is described as a combination of the likelihood of occurrence of the event and the severity of consequence, as shown previously in Table 7. The approach to risk analysis taken in this thesis was to estimate the likelihood of occurrence of ground impact and midair collisions without mitigation based on several assumptions of vehicle characteristics, accident scenarios, and operating characteristics. Ground impact was modeled using event tree analysis and a casualty expectation approach in Chapter 6. The parametric model was applied to vehicles from six different potential categories, and the variation of risk with geographic area of operation was also modeled. Midair collisions were modeled based on a gas model of aircraft collisions in Chapter 7. The model assumes the random location of a UAV in airspace. The variance in midair collision risk was investigated across the country and in the vicinity of jet and victor airways.

Regulatory guidance for the required level of safety of a UAV system is not yet defined. The principle of "first, do no harm" is often cited [54] based on the Hippocratic Oath administered to medical doctors. While this philosophy is attractive in principle, it is not explicit in providing the target levels of safety in system design. In terms of ground impact risk, the regulatory guidance and the empirical levels of risk are within an order of magnitude for both commercial and general aviation systems. On the other hand, the risk of midair collisions varies greatly depending upon vehicle class. For general aviation, the risk is greater than regulatory guidance for aircraft systems, except for the guidance for Class I general aviation aircraft.

By their nature, it is likely that unmanned aircraft will need to exceed the currently demonstrated levels of safety in manned aviation. In light of the uncertainty regarding target levels of safety for UAV system design and the difference between regulatory guidance and demonstrated levels of safety, an approach was taken in the risk analysis of UAV operations to investigate the differential risk posed by varying operations and vehicle parameters. The analysis is informed by the target levels of safety, but does not indicate system performance required to gain regulatory approval.

The quantitative analysis is useful for comparing potential operating strategies, reliability requirements, and mitigation possibilities for a broad range of UAV classes. The quantitative risk analysis techniques used for the preliminary hazard analysis provide an estimate of the average of each risk. The variability due to unknown parameters was not investigated. The analysis also does not directly include the effect of mitigation measures, or requirements due to public risk acceptance. Both may be critical in the regulatory process.

Chapter 6

Ground Impact Hazard Analysis

Ground impact was identified in Chapter 5 as a critical hazard in UAV operations. Whenever a UAV overlies a populated area a risk to the general public on the ground will be present. To investigate the influence of several factors of UAV operation on the risk of ground fatality, a model of UAV ground impact was created. The ground impact model utilizes event tree analysis and a casualty expectation approach to determine the total system reliability required to meet a designated target level of safety. The variation in system reliability required by area of operation and between different potential classes of UAVs was investigated.

6.1 Ground Impact Model

An event-based model was used to determine a probabilistic expectation of the number of fatalities per hour of operation of a UAV system. The casualty expectation approach was originally formulated and has been applied to determine the risk to the general public due to space launch activities [52,54]. It was also recently proposed for application to UAVs [56] concurrent with a preliminary presentation of the analysis conducted in this thesis [57]. The basis of the approach is in modeling the ground impact of a UAV by a sequence of events represented by an event tree, as shown in Figure 19. The branches of the tree represent different specific outcomes for the general categories shown above each branch, and the outcomes of different paths of the tree are shown to the right of the tree. The bottom line represents the failure path that results in a ground fatality.

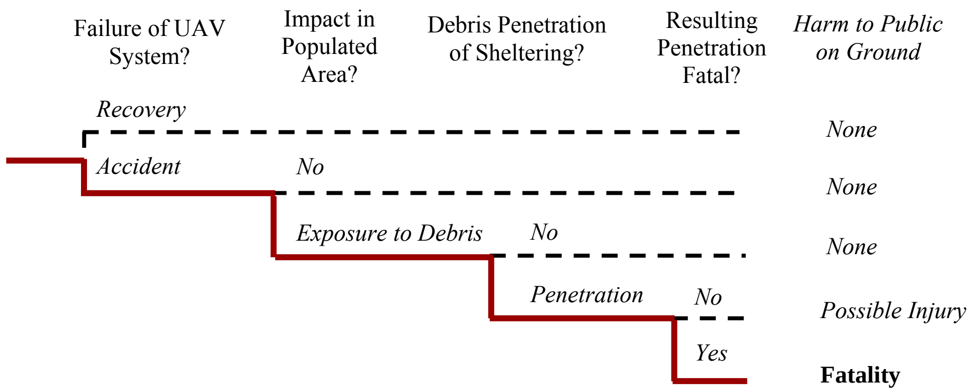


Figure 19: Ground Impact Event Tree

The event-based model first describes whether a failure of the UAV system has occured. If it has, then an accident has occurred that will result in an uncontrolled ground impact. The model then describes whether a person is located where the UAV impacts, and if the debris from the crash penetrates the sheltering in which the person is located. Probabilistic expectation of the serial combination of the four events describes the expected number of fatalities per hour of operation of the system, and is termed the expected level of safety (ELS).

Failures of the UAV system are modeled to occur at an average rate denoted by the mean time between failures, *MTBF*, indicating the reliability measure of the sytem. The expected number of failures per hour is the inverse of the term. Failures are measured as any general type that leads to an accident, including mechanical and software failures, human error, and combinations of events that result in a ground impact.

Ground impact of the UAV "exposes" the general public to potential harm, but does not necessarily directly result in a fatality. By this formulation, the UAV accident results in an average area of exposure for which the accident has effects, which can be thought of as the lethal debris area. This area is estimated by the term A_{exp}. The population who are impacted by the accident are said to be exposed to harm, and the expected number of people exposed is the product of the area of exposure and the population density of the area, ρ, measured in number of people per square foot. The probabilistic expectation assumes that the population is evenly distributed over the area of interest.

The ground impact model also incorporates population sheltering effects. This aspect of the model recognizes that not all UAV impacts are fatal. Debris generated by a

UAV accident must penetrate sheltering, such as vehicles, houses, or other buildings in which the general public is located, before coming into contact with a person. The proportion of time that the debris will penetrate shelter given exposure is modeled by the penetration factor, P_{pen}. It is assumed that if debris penetrates sheltering, then a fatality has occurred.

It should be noted that several design factors or operational requirements can mitigate the risk of occurrence of a ground fatality. They can affect any term of the event sequence shown in Figure 19, affecting debris size, penetration factor, or vehicle reliability. To capture the effects of mitigation, the term P_{mit} is included in the formulation, indicating the proportion of accidents for which mitigation prevents the occurrence of a ground fatality. With mitigation, the expected level of safety of the system is increased by *(1 minus P_{mit})*. For the analysis in this thesis, mitigation is not considered, and the term is set to unity. The resulting formulation for the expected level of safety of a UAV operation with respect to ground impact is given by Equation (1). Equation (1) is applied to determine the expected level of safety for several UAV classes in Section 6.3.

$$ELS=\frac{1}{MTBF}A_{exp}\rho P_{Pen}\left(1-P_{mit}\right) \tag{1}$$

6.2 Model Limitations

The model described by Equation (1) has several simplifying assumptions which impose limitations on its applicability. The model is based on the event sequence shown in Figure 19, therefore other failure modes that may result in ground fatalities, such as the loss of a part or collision with bystanders during a controlled landing are not considered. The model also does not consider parameter uncertainty, as it only calculates the expected rate of occurrence of ground fatalities.

The model does not account for variability in the population density of the areas overflown. According to FAA guidance, the expected level of safety is calculated as the probability of occurrence for an average flight divided by the time of an average flight. Therefore, the expected level of safety over several flights would need to take into account the average population density overflown if the UAV flies over areas of several different densities. The model formulated based on the event sequence of Figure 19 represents the instantaneous risk of operating over a region of the given density.

Population sheltering characteristics will vary with the time of day and the day of the week, as people participate in different activities such as work, school, or recreation. Sheltering characteristics will also vary with location in the United States depending upon the type and distribution of structures at that location. To maintain consistency across the United States, the penetration factor was estimated for each vehicle class, and temporal and geographic variances were not directly incorporated into the model.

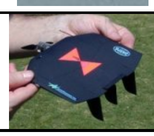
Due to uncertainties in the model, and these limitations, the results are useful for comparisons between vehicle classes and identification of general trends across the United States. To determine the expected level of safety of a specific unmanned system, a more detailed model of the UAV's operations and population sheltering characteristics in the vicinity of operation would be required.

6.3 Model Application

Although the target level of the safety required by regulations is uncertain, the ground impact risk can be communicated as the system reliability required to meet the target level of safety. In this method, the expected level of safety of the system – *ELS* in Equation (1) – is set equal to the target level of safety. Next, the variation of risk is investigated as a function of the mean time between failures, *MTBF* to meet the required target level of safety. The target level of safety used was 1×10^{-7} fatalities per hour of operation, which corresponds to the most stringent FAA guidance on the target level of safety for hazardous events. Using the model in this form allows a more intuitive measure of the implications of regulatory requirements on vehicle reliability requirements.

The ground impact model of Equation (1) was applied to six UAVs from the Heavy, HALE, MALE, Tactical, Mini, and Micro classifications. The reliability required was calculated parametrically based on representative vehicles for the UAV class. A summary of the parameters of the model are shown in Table 11. The area of exposure of the UAV was estimated as the planform area of the UAV, reflecting the average area of lethal debris due to an uncontrolled crash. The true lethal area may vary depending upon the nature of the accident and the design and configuration of the aircraft. Population density data were used from the 2000 U.S. Census [58] for tract groups in all 50 United States.

Table 11: UAV Classes for Ground Impact Analysis

Representative Vehicles		Weight	A_{exp}	Estimated P_{Pen}
Heavy		602,500 lb	7700 ft^2	100%
HALE		25,600 lb	900 ft^2	90%
MALE		2,250 lb	360 ft^2	60%
Tactical		351 lb	30 ft^2	25%
Mini		9.6 lb	14 ft^2	10%
Micro		0.14 lb (2.16 oz)	0.26 ft^2	5%

The probability of penetration, P_{pen}, depends on many factors, including the energy of the vehicle, the amount of energy several structures can withstand, and the distribution of people within those structures. For this general approach, a single factor estimate of the probability of penetration was used. The probability of penetration shown in Table 11 was estimated based on the kinetic energy of the aircraft in cruise, and the realization that the factor will vary from 0% to 100% from low to high energy impacts.

6.4 Results

The required system reliability to meet an assumed target level of safety of 10^{-7} fatalities per hour of operations was calculated based on Equation (1). The ArcMap® software package [58] was used to plot contours of equal reliability required for the five aircraft in Table 11. The results of the analysis are shown in Figure 20 through Figure 25 on the following pages. Reliability required is divided into five divisions in the legend. Each division spans two orders of magnitude in mean time between failures. The legend symbology and reliability ranges remain constant across the figures. The contours of reliability illustrate both the spatial variation and variation between vehicle classes. Within each figure, differences in reliability required are shown corresponding to area of operation, and differences between figures are due to changes in the parameters of the vehicle class. The proportion of the U.S. area for which the reliability required is within the given range is also tabulated in the legend. Figure 26 summarizes the area of the U.S. at each reliability level for the six UAV classes.

By area, 6.3% of the United States reported in the census is completely unpopulated. Based on Equation (1), no casualties are expected regardless of how often a UAV crashes over this area. Correspondingly, by this method of communication, zero hours are required between failures to operate at any given target level of safety. This is informative of the rationale of testing UAVs and manned military aircraft in some of these areas which are essentially deserted. The areas of zero population density show up most apparently as an anomaly in Figure 25 for the Heavy class of UAVs, where there are apparently no regions of the country that can be operated at from 1 to 100 hours between failures, but 6.3% that can be operated at less than 1 hour between failures. This does not reflect an error in the calculation, but a characteristic of the population density data.

It should be noted that some UAV ground impacts may be categorized as catastrophic if they result in a large number of fatalities. In this case there would be an increase in the reliability required beyond the values shown in the figure. It should also be noted that this analysis did not include possible mitigation measures, such as flight termination systems, emergency parachute recovery systems, or other measures that would lessen the severity of ground impact. Inclusion of such capabilities in aircraft could also be used to achieve an acceptable level of safety.

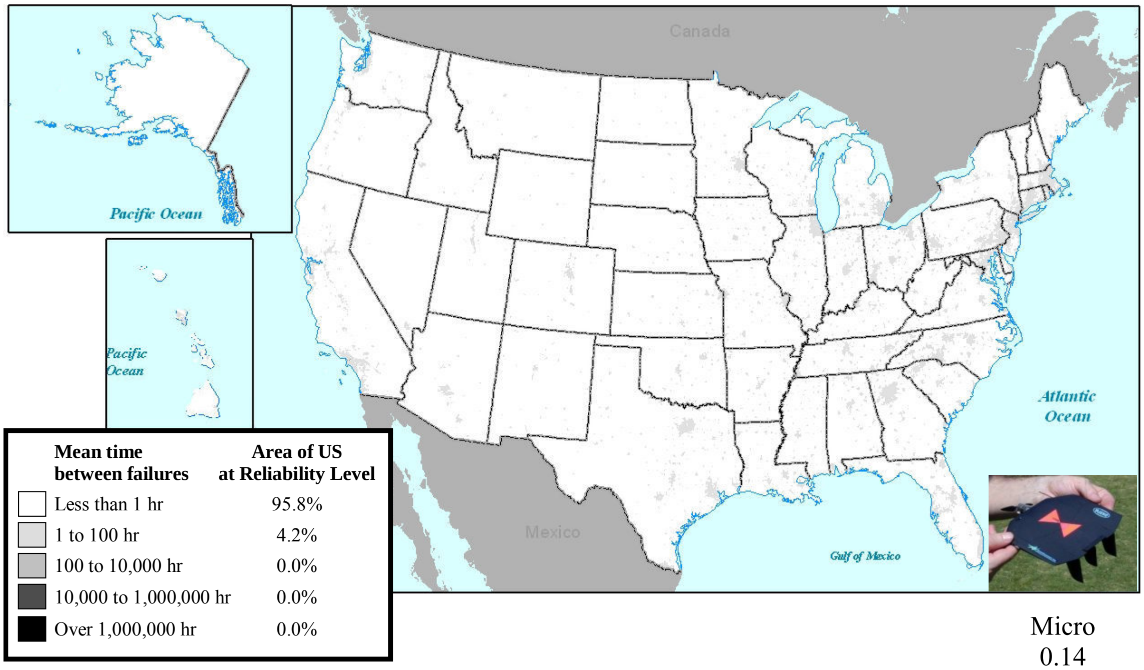


Figure 20: Micro UAV Reliability Required to Meet a Target Level of Safety of 10^{-7} fatalities / hr

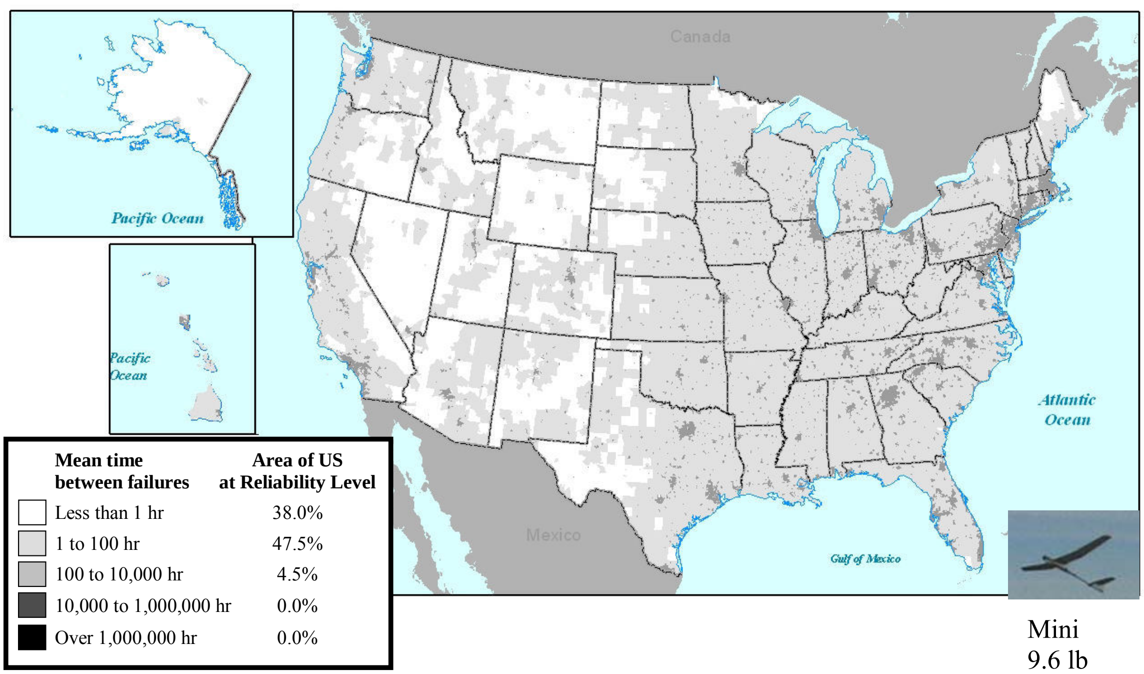


Figure 21: Mini UAV Reliability Required to Meet a Target Level of Safety of 10^{-7} fatalities / hr

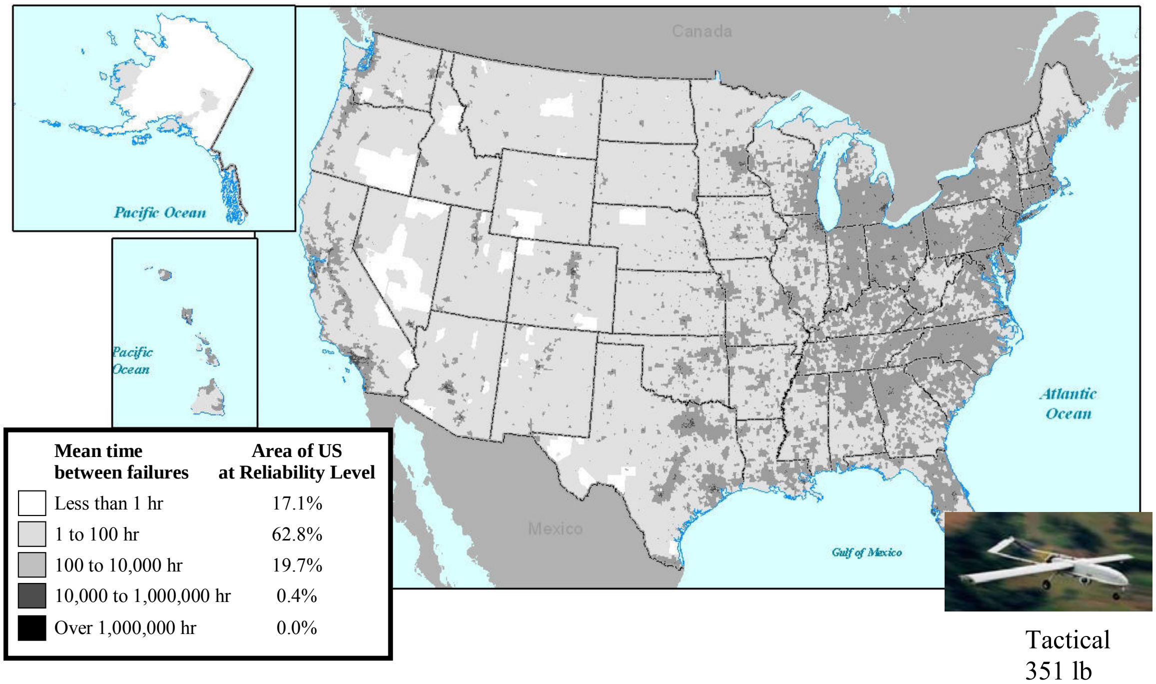


Figure 22: Tactical UAV Reliability Required to Meet a Target Level of Safety of 10^{-7} fatalities / hr

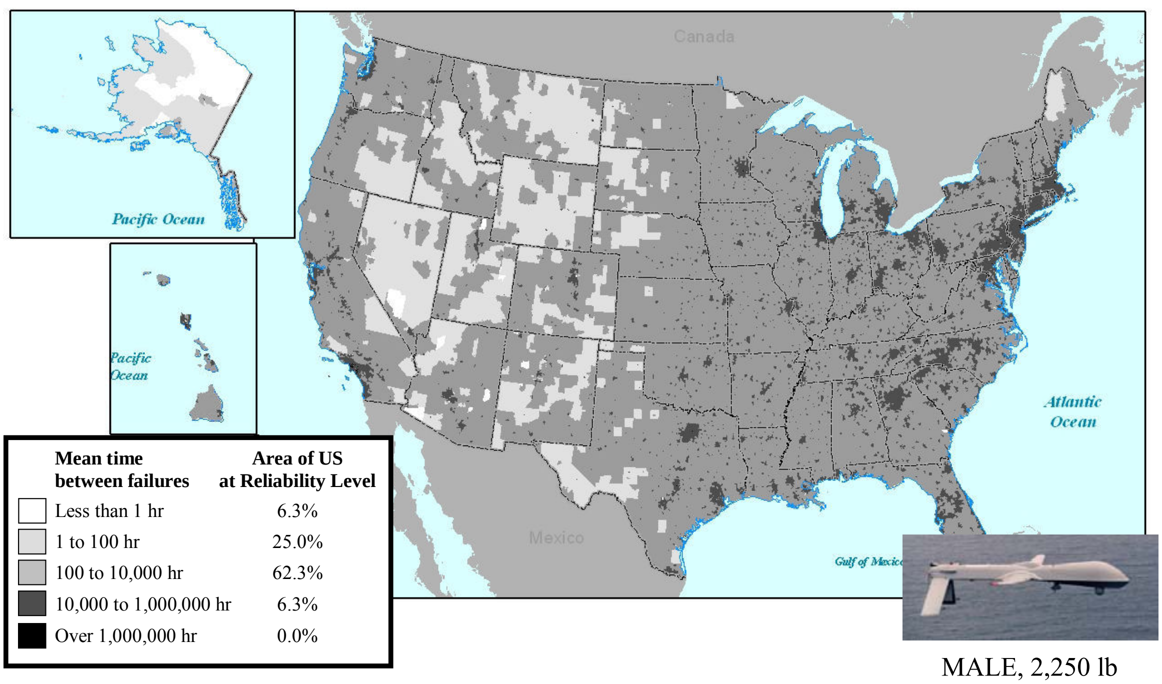


Figure 23: MALE UAV Reliability Required to Meet a Target Level of Safety of 10^{-7} fatalities / hr

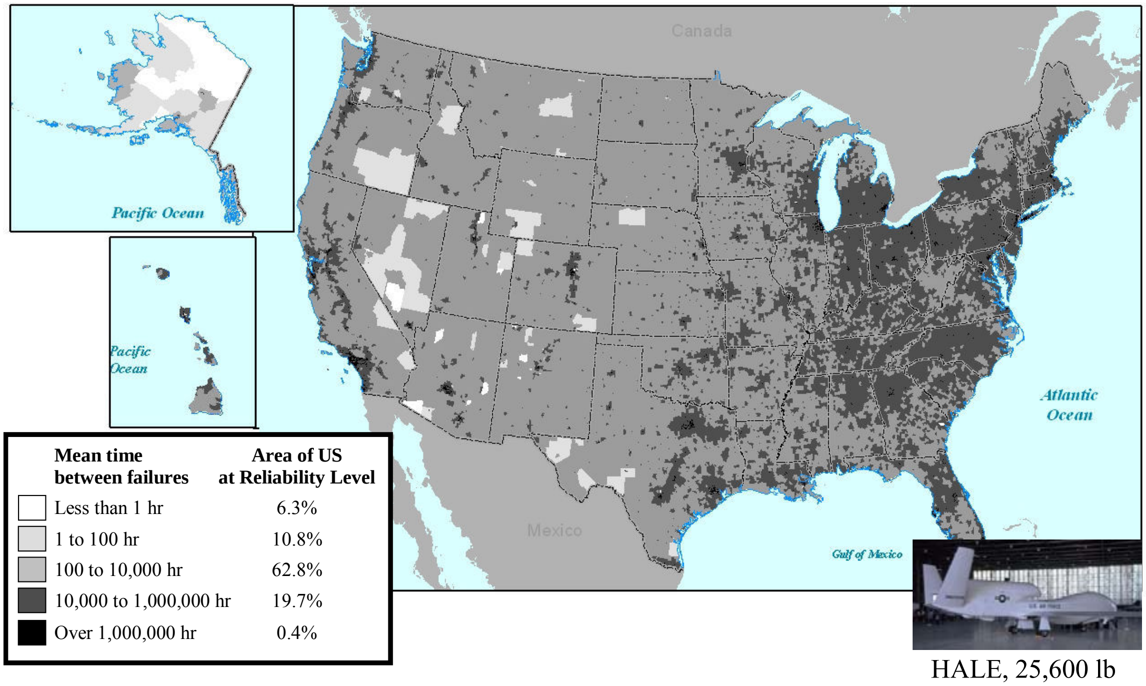


Figure 24: HALE UAV Reliability Required to Meet a Target Level of Safety of 10^{-7} fatalities / hr

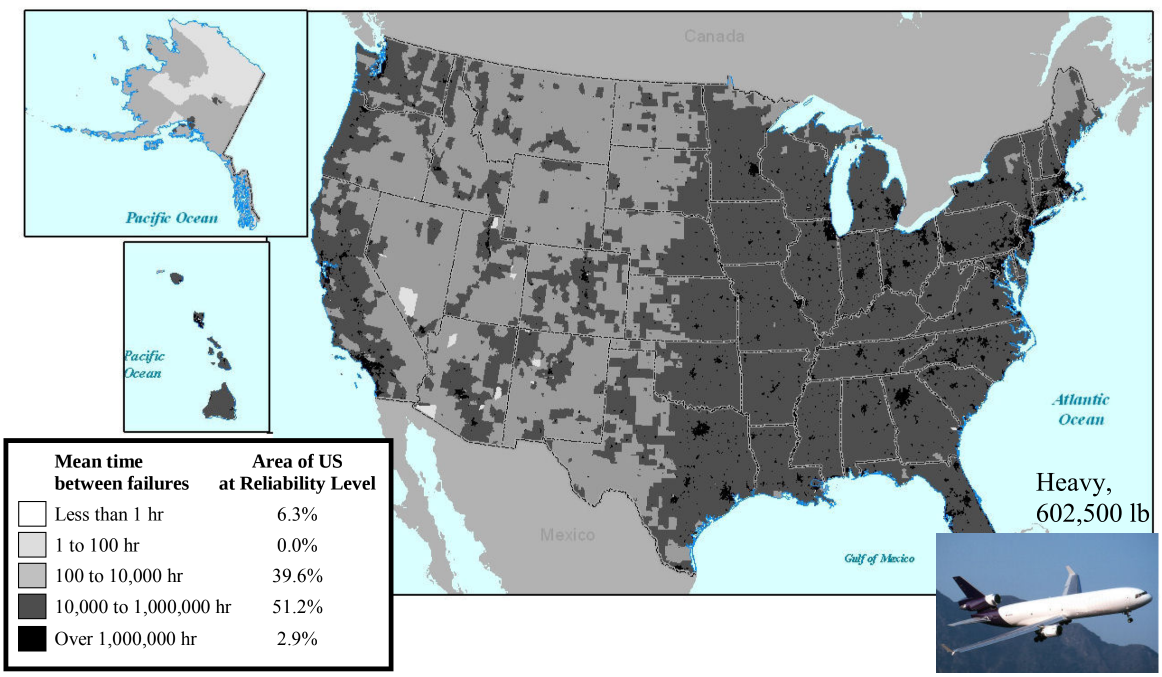


Figure 25: Heavy UAV Reliability Required to Meet a Target Level of Safety of 10^{-7} fatalities / hr

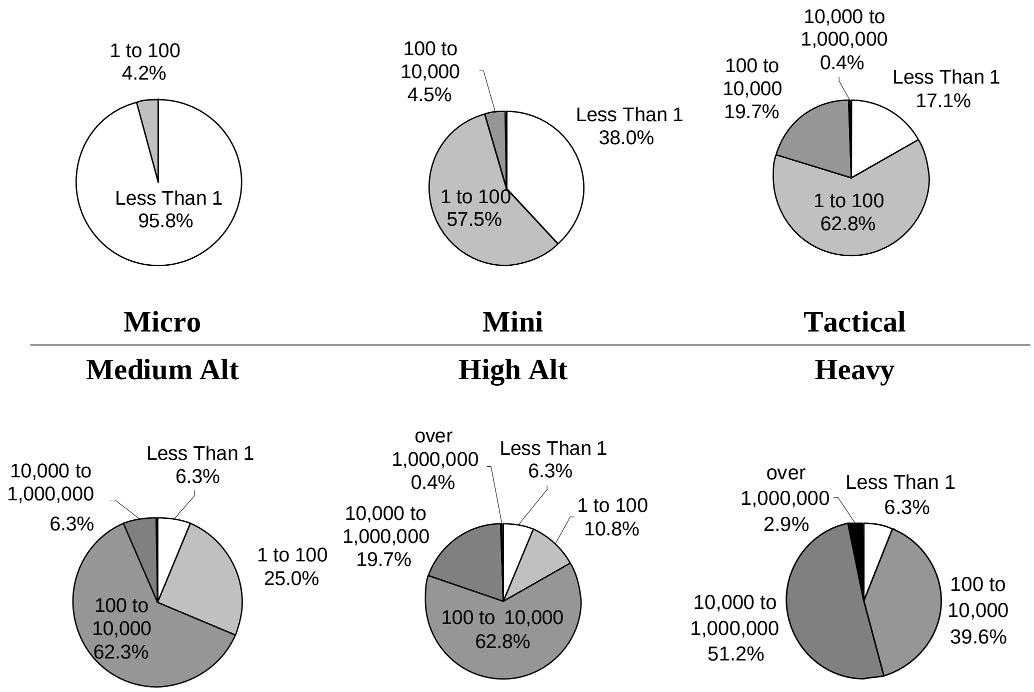


Figure 26: Proportion of U.S. Area at Required Reliability Level for Different Classes of UAVs

6.5 Conclusions

The first trend evident with respect to each class of UAV is the significant increase in reliability required to operate over metropolitan areas. One can easily identify major cities such as New York, Chicago, Dallas, Denver, and Los Angeles by the two order of magnitude increase in the required reliability. Within UAV classes, the increase in risk to the general public is solely due to the increased population density in metropolitan areas. The second trend evident is the increase in required reliability with increased vehicle mass. Comparing between figures shows the increase in reliability requirements as vehicle mass increases. For several classes, the percentage of the country that can be operated at different reliability levels is discussed. This is meant to facilitate comparison of the risk variation, not to indicate that operations should be restricted bases solely on population density.

There is a relatively low risk due to the operation of Micro UAVs over the majority of the country. A mean time between accidents on the order of 1 to 100 hours is required over 4% of the country, which is likely to be a conservative estimate due to the high probability of penetration assumed in the analysis. For mini UAVs, operation over 95% of the country could be achieved, with a low reliability requirement. To operate over highly populated areas, additional mitigation measures that lessen the impact if an accident occurs may need to be employed. Operation of these types of aircraft is potentially allowable with few reliability requirements, even over densely populated areas of the country.

Tactical and MALE UAVs represent an intermediate level of risk. If the accident rates of current unmanned systems can be maintained, then it may be possible to operate both classes of vehicles over the majority of the country without additional mitigation. Over highly populated areas, increased reliability or additional mitigation would be required. HALE UAVs would need to meet reliability levels of current manned military or general aviation aircraft, on the order of 100,000 hr between accidents, to overfly 20% of the country.

The class of Heavy UAVs displays a high reliability required for operation of a large portion of the United States. By its size and character of operation, the Heavy class presents a similar risk to the public on the ground as existing commercial aircraft. Therefore, to overfly populated areas, it would have to meet the current reliability of commercial aircraft, over one million hours between accidents. The safety of this class of UAVs may need to be initially demonstrated over the oceans from coastal airports, limiting the general public's exposure to risk.

There is a broad variation in reliability required between vehicle classes and area of operation. Therefore, risk mitigation measures and possible operations will vary between classes. In order to be operated over the United States, large mass UAVs will need to achieve high reliability with respect to possible ground impact. For intermediate mass UAVs, it may be possible to segregate operations away from high population areas, and add additional requirements to achieve operations across the country. As mass further decreases, there is a threshold where it may be possible to operate mini and micro UAVs over the majority of the United States with few mitigation measures or reliability requirements.

Chapter 7

Midair Collision Hazard Analysis

The second critical hazard of UAV operation identified in Chapter 5 is midair collision with another aircraft. To understand the factors influencing the unmitigated or ambient risk of this event, a model of midair collisions between UAVs and other aircraft was developed based on the gas model of aircraft collisions. The model incorporates air traffic density data from an FAA surveillance source to determine the expected number of collisions per UAV flight hour.

The model assumes random operation of a UAV without traffic avoidance capability. This type of operation most appropriately describes the operation of small UAVs, as discussed in Chapter 3. For larger aircraft, surveillance is likely to be required to prevent collisions. The safety of operations under positive control would need to be captured by separate models of aircraft collisions that consider avoidance capability. For those classes of aircraft, this analysis represents the ambient risk due to random operations, with additional safety added by avoidance maneuvers.

The expected level of safety was investigated in several regions of the NAS, first averaged from sea level to 50,000 ft, and then around jet routes and victor airways. The analysis provides insight into the variation of collision risk with respect to structure of the NAS and the possibility of low-risk operating strategies.

7.1 Collision Rate Formulation

The expected rate of midair collision between a UAV (the “threat” aircraft) and other (“threatened”) aircraft was modeled based on a gas model of aircraft collisions [59]. In this model, the UAV location is assumed to be equally likely in the volume of airspace under investigation. Its velocity is also assumed to be small compared to the threatened aircraft. When threatened aircraft fly through the airspace under investigation, they extrude potential collision volumes. The collision risk, described by the expected number of collisions per hour of UAV operation is the ratio of volume extruded by threatened aircraft per hour to the volume of airspace.

The midair collision model is illustrated in Figure 27. Each aircraft flies a distance, d_i through the airspace segment under consideration. Each threatened aircraft also has an area of exposure, A_{exp}, representing the contact area that is vulnerable to a collision. In this analysis, the area of exposure was estimated as the frontal area of a mid-sized commercial aircraft (the Boeing 757), approximately 560 ft^2. The area of exposure also does not vary significantly with UAV class, assuming the UAV area is small compared to the threatened aircraft.

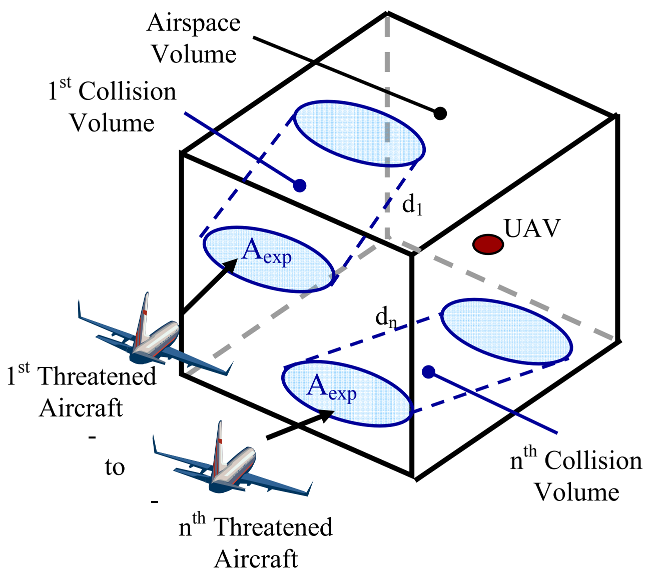


Figure 27: Midair Collision Model

The area of exposure, extruded over the distance flown represents a potential collision volume. The total collision volume for threatened aircraft is the area of exposure times the sum of the distances flown by aircraft in the airspace under consideration. Because an expected collision occurs if the exposure volume overlaps with the UAV, the expected number of collisions is equal to the ratio of total collision volume to the volume of airspace. To generate a sufficient sample of the behavior of air traffic, the total distance flown within the airspace under consideration is calculated over a given period of time, *t*. The expected collision rate is equal to the expected number of collisions divided by time.

Although a potential collision may occur, there is the possibility that it does not result in fatality, either by direct avoidance of the collision, or by mitigating the magnitude of the collision. Recognizing this, an additional mitigation term is included in the model, $P_{fat|coll}$, which is the conditional probability that the collision is fatal given that there was an expected potential collision. For the baseline analysis, mitigation was not included. Therefore the mitigation term is set equal to unity. Combining all terms gives the expected level of safety in terms of fatal accidents per hour, shown in Equation (2).

$$\mathrm{ELS} = \frac{A_{exp} d}{Vt} P_{fat|coll} \tag{2}$$

7.2 Data Source

In order to investigate air traffic patterns in the NAS, data on all surveilled flights over the U.S. for one day in January 2004 were obtained from the FAA Enhanced Traffic Management System (ETMS). The data are organized as position and altitude surveillance gathered from both primary and secondary radar returns and represent all aircraft tracked by air traffic control. The data were processed and filtered into usable form according to the methodology developed by Mozdzanowska [60].

Where radar coverage is not available, especially at low altitude where obscured by terrain, flight trajectories are not included in the database or are incomplete. Some vehicles which are not tracked by the system, such as ultralights and some general aviation aircraft are not included. Therefore, the dataset represents an under-sampling of traffic density in the NAS. Additionally, as traffic density is averaged over 24 hours in the analysis, the results may also represent an underestimation of the expected level of safety at peak times due to temporal variation in traffic.

7.3 Average Midair Collision Risk over the United States

To develop a preliminary estimate of midair collision risk, the variation of expected level of safety spatially over the United States was investigated, assuming that the UAV was equally likely to be located anywhere from sea level to 50,000 ft (neglecting the effects of land elevation). The model of midair collisions given by Equation (2) was applied to all air traffic from sea level to 50,000 ft over the United

States. The resulting variation in expected level of safety over several regions of the country is shown in Figure 28.

The results highlight several spatial trends in traffic density, and proportionally, expected level of safety. First, the majority of the collision risk is concentrated over metropolitan areas with major airports. Second, the structure of the NAS is evident, with large traffic density along several well-traveled routes and heavily utilized regions of airspace.

The expected level of safety calculated using this method does not adequately represent the behavior of traffic. The structure of the NAS is such that the majority of traffic operates on flight levels and along airways. This concentrates traffic in local regions of increased density in ways that are not directly captured by this method. Therefore, in the next section, a methodology is introduced to investigate the variation of collision risk with airway structure.

Figure 28: Average Expected Level of Safety from 0 to 50,000 ft

7.4 Airway Structure

Traffic is not uniformly distributed in the NAS. Therefore averaging collision risk within a cube of airspace did not adequately represent the nature of collision risk. The structure of the NAS creates locally high densities of aircraft along airways and on flight levels, and a lower density in other regions. The risk to other air traffic posed by UAVs may vary significantly depending upon the type of operations allowed for UAVs.

For example, it may be possible to significantly reduce the ambient risk of UAV operation by requiring the UAV to be operated away from airways and major flight levels.

7.4.1 Regions Investigated

To determine the amount of variation in the expected level of safety of UAV operations with respect to airspace structure, traffic density was investigated in the vicinity of jet routes and victor airways in the United States. Conceptual areas of traffic density and behavior in the vicinity of airways were identified and are shown in Figure 29. The four areas of operation for each type of airway form a matrix, described by either being on or off a major flight level (in the altitude dimension), or on or off the airway (in the cross-track dimension).

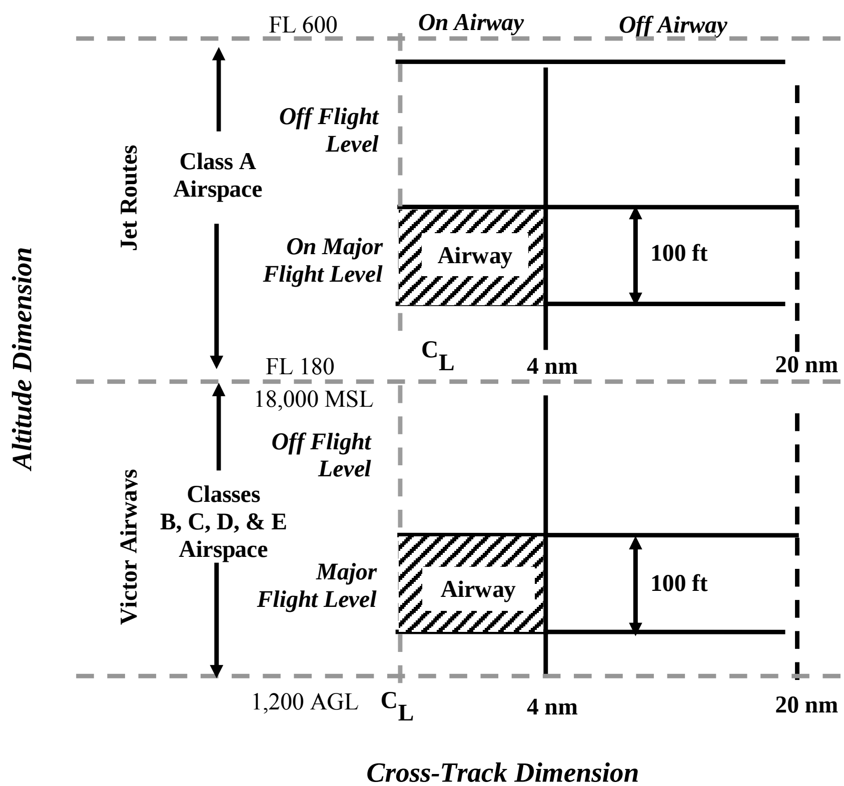


Figure 29: Conceptual Areas of Operation in the Vicinity of Airways

The width of a victor airway is defined by the FAA as 4 nm from centerline to boundary [29]. Jet routes do not have a defined width, but 4 nm was used to remain consistent between analyses. Victor airways and jet routes are defined between navigational aides, with intersections and intermediate points designated by reporting fixes. Traffic density was analyzed within 20 nm on either side of the airway centerline, and results will be shown within 15 miles of the centerline to remove boundary effects. Expected level of safety beyond 20 nm from the airway centerline was not investigated due to computational processing limitations.

Traffic density, and therefore collision risk, is expected to be highest on major flight levels and within the airway boundaries, reflecting the operation of the majority of aircraft navigating along airways at a constant altitude. Traffic density is expected to be lowest both off flight levels and away from airway boundaries. Traffic in this region is expected to be in transition between flight levels and navigational fixes (in two dimensions). The remaining two regions, where transition is expected in only one dimension, should have densities somewhere in between the other regions.

7.4.2 Data Transformation

To adequately capture behavior within the regions shown in Figure 29, flights from the ETMS data source were transformed from latitude, longitude, and altitude into local airway coordinates for each airway in the vicinity of the flight path. The local airways coordinates are measured by cross-track deviation from the airway centerline, altitude, and length along the airway. A three-dimensional interpolation was then performed to determine the length traveled by the flight along the airway in bins measuring 0.25 nm in width and 100 ft in altitude. Distance flown was aggregated for all aircraft by airway and bin size. The result for each airway was a measure of the average density of traffic in each bin. The midair collision model was then applied and the expected level of safety was averaged along the length of all airways jet routes and a subset of victor airways in the NAS.

7.5 Midair Collision Risk in the Vicinity Airways

7.5.1 Jet Routes

To investigate the variation of collision risk around jet routes, air traffic density was aggregated over all jet routes in the United States, using the method described in the previous section. This included 263 routes, totaling 184,000 nm in length. The expected level of safety in terms of collisions per hour was calculated using the midair collision model of Equation (2). The variation in expected level of safety in the vicinity of airways is shown in several dimensions in Figure 30. To discuss general trends in risk around airways for a range of UAV operations, the expected level of safety was averaged over the length of all jet routes. Density may vary locally along individual airways due to the behavior of traffic in the area.

Figure 30a shows the contours of expected level of safety with respect to both cross-track deviation and altitude. The regions around the airway identified in Figure 29 are evident in the contour plot. Each dimension is further analyzed in Figure 30b to Figure 30d. High collision risk is washed out in Figure 30a, denoted by the largest and darkest bin representing an expected level of safety at and above 1×10^{-6} collisions / hr. For the baseline case without mitigation, there are few regions in the vicinity of airways with an expected level of safety below the FAA's most stringent target level of safety of 10^{-9} collisions per hour.

To examine the variation of collision risk with altitude while operating within airway boundaries, the average collision risk within 4 nm of the airway centerline along flight levels is shown in parts b and c of Figure 30. Jet routes show a clear stratification of density, and therefore expected level of safety along major flight levels. The 1,000 ft separation between flight levels from FL 180 to FL 290 and 2,000 ft separation from FL 290 to FL 450[1] are apparent in both parts b and c of Figure 30. The highest average expected level of safety on an airway is at FL 370, and is approximately 4×10^{-5} collisions / hr. The lowest expected level of safety is on the order of 10^{-9} above FL 430.

Parts d and e of Figure 30 show the variation of collision risk with distance from the airway for several altitudes on and off major airways respectively. There is a consistent pattern for all altitudes under investigation, with a large increase in the expected level of safety within approximately 2 nm of the airway centerline, and a constant expected level of safety outside of the airway boundaries. Expected level of safety is on the order of 2×10^{-7} collisions / hr, off airways and off major flight levels.

There is a two order of magnitude difference between regions on major flight levels and airways, and off flight levels away from the airway. The overall collision risk

[1] Reduced Vertical Separation Minima (RVSM) had not been enacted at the time the data were collected. On January 20, 2005, the separation between flight levels from FL 290 to FL 410 was reduced to 1,000 ft.

estimates do not meet the FAA's most stringent target level of safety, but operations off major airways could potentially be conducted with additional avoidance capability below the currently demonstrated level of safety with respect to midair collisions. Additionally, operations above FL 430 present a very low midair collision risk.

It should be noted that the estimated expected level of safety does not reflect any avoidance maneuvers undertaken by the aircraft, and therefore represents the ambient risk due to air traffic. Additional risk mitigation measures and positive separation of aircraft further reduce collision risk.

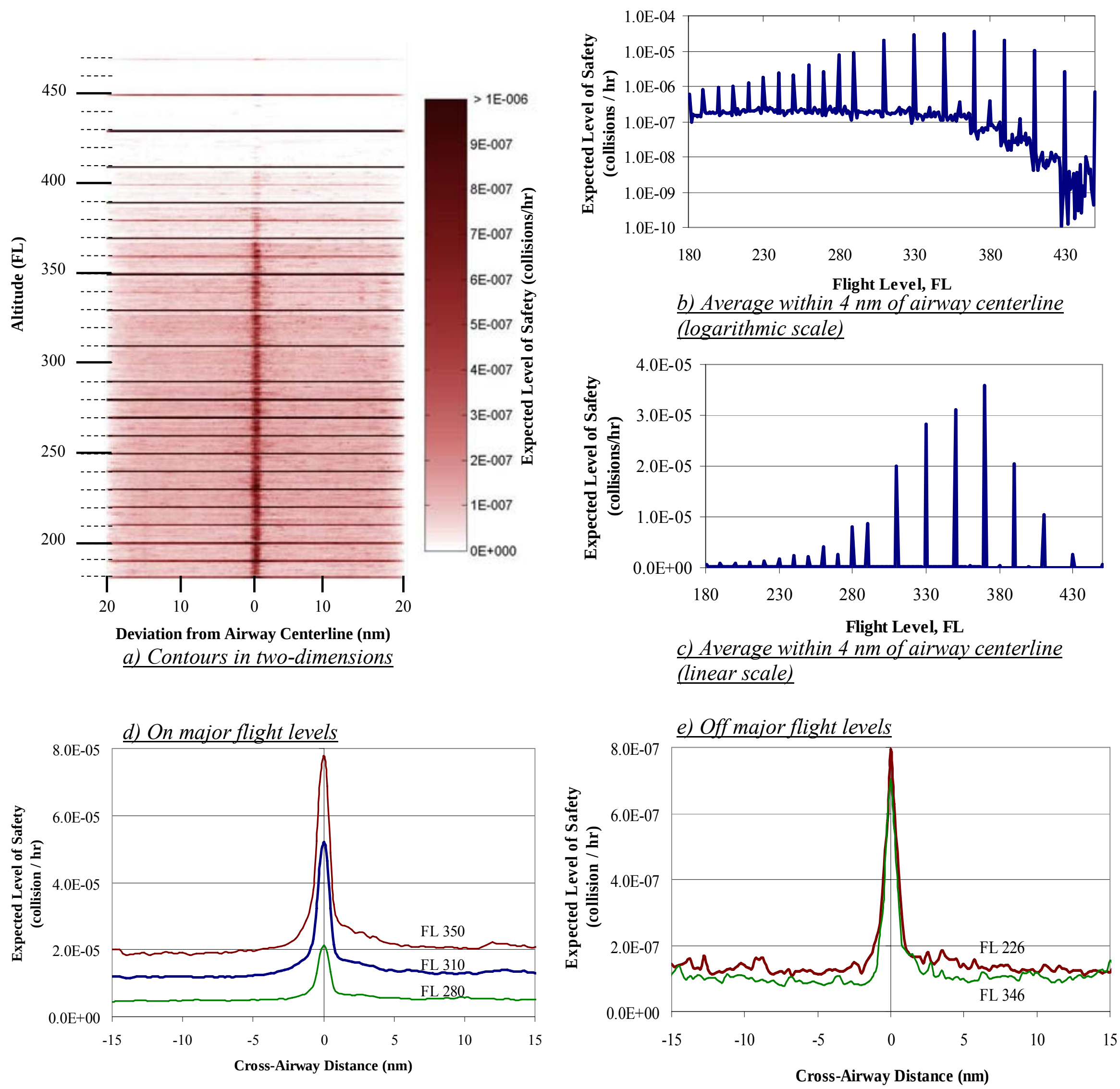


Figure 30: Average Expected Level of Safety in the Vicinity of all Jet Routes in the United States

7.5.2 Victor Airways

To adequately capture the behavior of air traffic around victor airways, it was necessary to select an area of the country with sufficient radar coverage at low altitude. It was also desirable to find a region with a high density of air traffic. Under these criteria, flight traffic in the vicinity of victor airways within the Northeast (NE) Corridor of the United States was analyzed, extending from south of Washington, DC to north of Boston, MA. This region included portions of 102 separate airways, totaling 13,000 nm in length. To maintain general applicability to a wide range of UAV operations, the expected level of safety was averaged over the length of all victor airways in the northeast.

The average expected level of safety was calculated based on the midair collision model of Equation (2). The variation in expected level of safety in the vicinity of airways is shown in several dimensions in Figure 31 averaged over all victor airways in the NE corridor. Density may vary locally along individual airways due to the behavior of traffic in the area and may be lower in other regions of the country where there is a lower density of aircraft. The expected level of safety over victor airways exhibits similar stratification to jet routes in both dimensions, as shown in Parts a & b of Figure 31.

Figure 31c shows the variation of expected level of safety with altitude, averaged within 4 nm of the airway centerline. Unlike traffic around jet routes, the expected level of safety does not vary significantly with altitude at the lower boundaries of airspace, below 5,000 ft. This trend is likely due to the behavior of traffic in the vicinity of airports in the region. The majority of traffic at low altitudes is likely to be maneuvering significantly during departure and arrival, and may not be operating along airways for VOR approaches in the traffic pattern. High density likely extends to ground level, but the traffic dataset is under-sampled in this region due to terrain blockage of radar returns. Above 5,000 ft in altitude, 1,000 ft separation between flight levels is again apparent, and maximum collision risk is on the order of 7 x 10^{-6} collisions / hr at 18,000 ft.

Figures 9d and 9e show the variation of the expected level of safety with distance from the airway for sample altitudes on and off major airways respectively. Again, the results are dissimilar to jet routes at low altitude, with little variation in risk with distance from airway centerline. As altitude increases, there is an increase in collision risk within approximately 2 nm of the airway centerline. The expected level of safety off airway and off major flight levels is on the order of 3 x 10^{-7} collisions / hr, at both 6,200 ft and 13,300 ft. This is of similar magnitude to the ambient risk off major altitudes and off airway for jet routes.

Again similar to the expected level of safety in the vicinity of jet routes, there is a difference of two orders of magnitude between regions on major flight levels and on airways, and off flight level away from the airway. The overall collision risk estimates do not meet the FAA's most stringent target level of safety. However, it should be noted that the risk estimated for victor airways do not reflect any avoidance maneuvers undertaken by the aircraft. In areas where the ambient risk is high, methods for avoiding collisions with other aircraft are likely to be required to meet an acceptable level of safety.

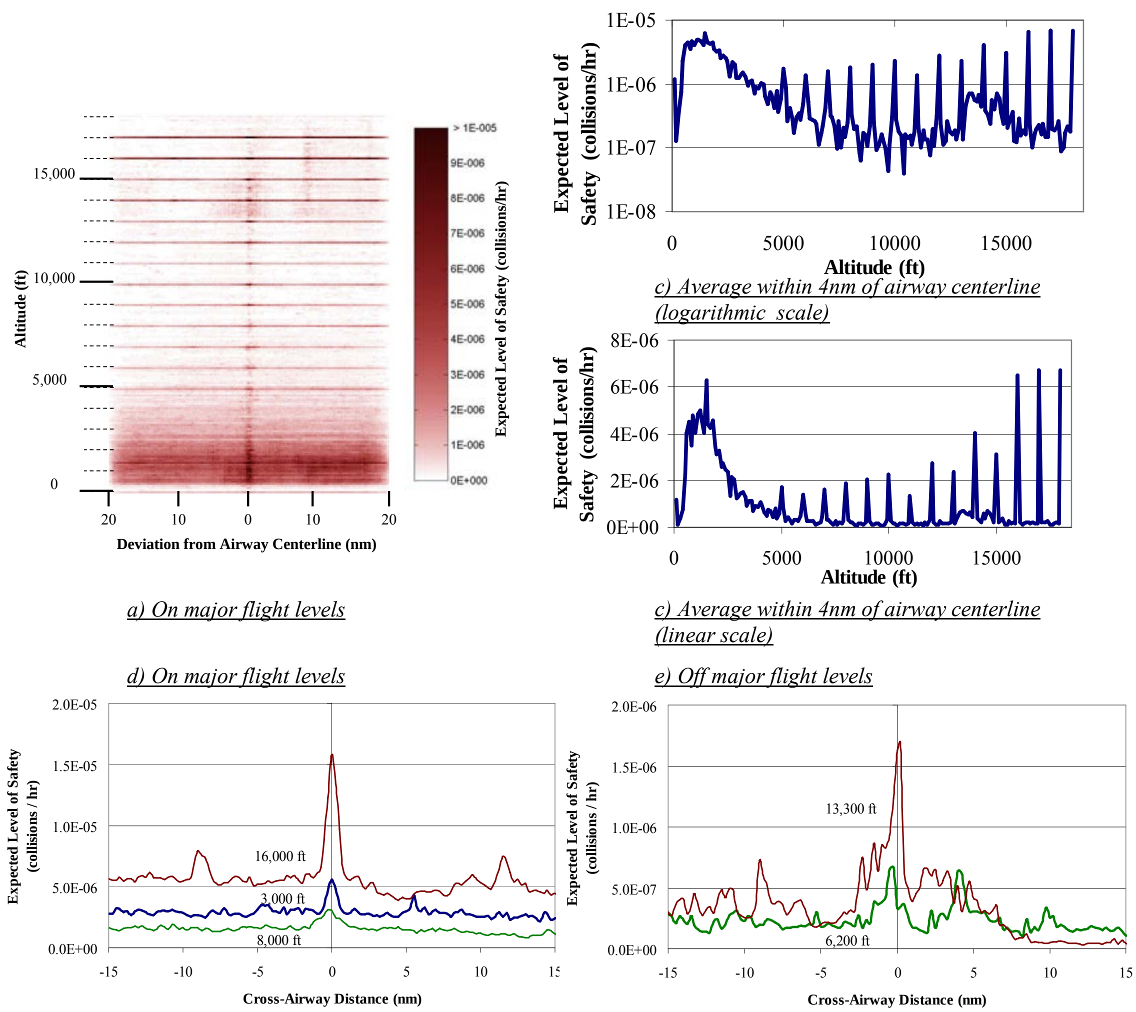


Figure 31: Average Expected Level of Safety in the Vicinity of Victor Airways in the NE Corridor

7.6 Conclusions

Under the assumptions of this analysis, the expected level of safety for unmitigated UAV operations in the airspace follow similar trends in the vicinity of jet routes and victor airways. There is a difference of two orders of magnitude between operations on major flight levels and on airways and off major flight levels and off airways. The expected level of safety on the former is on the order of 10^{-5} collisions / hr and on the latter, 10^{-7} collisions / hr. Below 5,000 ft, there are not a significant variation in traffic density, and therefore collision risk between major flight levels.

The trends in collision risk indicate that positive separation measures are likely to be required for all UAVs that operate within the boundaries of airways and on the same flight levels as current traffic at both high and low altitudes. This may either be provided by air traffic control or by a form of active collision avoidance by the UAV system. For an initial operating strategy, it is possible to operate UAVs between flight levels where the ambient traffic densities are low, with limited forms of collision avoidance mitigation. This mitigation may be in the form of segregation by air traffic control, or a lesser capability of the UAV system to avoid other traffic. This strategy does not generally appear to be feasible below 5,000 ft, or in local areas where there is a significant amount of air traffic in transition. At lower altitudes, local ground radar or line of sight collision prevention may be useful mitigation measures for preventing midair collisions.

Operations away from airways and away from major flight levels have the lowest risk. Without mitigation, the ambient collision risk is on the order of 10^{-7}, which is the currently experienced rate of midair collisions in general aviation aircraft. Based on the model, there is the opportunity to operate small UAVs without collision avoidance systems in these regions but with other potential mitigation measures.

Another low risk area of operation exists above the majority of commercial air traffic. High altitude, long endurance aircraft could be introduced above FL 500 in the region of uncontrolled airspace. Sufficient safety procedures would need to be crafted for the ascent and descent of the UAV, but onboard collision avoidance capability may not be required within the system.

Chapter 8

Ground Impact and Midair Collision Risk Mitigation

8.1 Need for Mitigation

The risk analyses performed for ground impact in Chapter 6 and midair collisions in Chapter 7 described the effect of several factors in vehicle design and operation that influence the ambient risk posed by UAV operations in the NAS. The analysis did not include the effect of mitigation measures, or measures that are further utilized in a system to reduce risk. The results of the risk analysis highlight the necessity of mitigation measures that reduce both the risk of ground impact and midair collision. When mitigation is required, there are a range of potential measures that can be implemented depending upon vehicle class, type of operation, and the level of safety required.

8.2 Risk Mitigation Strategies

There are several mitigation strategies that can be employed to further reduce risk both to the general public on the ground and to the traveling public in other aircraft. Mitigation measures were previously discussed in Chapter 4 in the context of current rules and regulations governing unmanned kites, balloons, and rockets, and model aircraft. In this section, some potential strategies for mitigating ground impact and midair collision risk are introduced and discussed.

8.2.1 Possible Mitigation Measures of Ground Impact Risk

A) Reduce the exposure to risk of the public on the ground

UAVs expose the general public to potential harm whenever they are flown over a populated area. Therefore, one mitigation measure is to limit the operations of the UAV to reduce exposure of the public on the ground to risk. This measure ensures that any potential failure will be less likely to result in a ground fatality because it is less likely that the UAV will impact a person. There are several potential approaches to accomplish this mitigation strategy. The approaches vary in how they limit the operation of the UAV.

One potential approach is to limit the operation of UAVs to sparsely populated areas, or away from major population centers, depending upon a threshold population density. This is currently utilized for experimental test flights of military aircraft and some UAV operations by limiting to restricted airspace or unpopulated test ranges. A degree of population protection could also be accomplished by limiting operations near airports, as airports are generally located near population centers. This measure protects the public from harm, but also restricts UAVs from operations where they may be most useful.

A second approach is to ensure local control over the exposure of risk to persons on the ground. If it is desired to operate over an urban area while also reducing population exposure, there is a possibility to utilize a highly precise navigation system that limits the operation of the aircraft to designated areas of low risk. The UAV could be operated in such a way to ensure that it is always over locally sparse population areas or areas where people are sheltered from harm. For example, the UAV's flight path could be limited to operation over waterways, undeveloped land, or above buildings with sufficient sheltering to protect the building occupants from harm.

B) Ensure UAV System Reliability

The two primary causes attributed to a significant portion of current UAV accidents are electromechanical failure and human error [61]. Reducing the rate of component or system failures reduces the potential for an accident. Mitigation strategies in this area ensure greater system reliability. Improving training and facilitating operation can also reduce the amount of human errors that result in system failures. The increased utilization of software in UAV systems will require several measures to ensure that the software contributes to system reliability.

C) Facilitate Safe Recovery from Failures

Methods can also be utilized to ensure recovery from mechanical or system failures, should they occur. By recovering from failures, operation of the system can continue with safety margins reduced, or a sufficient level of control can still be exercised to further mitigate the effects of the failure. Implementing recovery mitigation requires both the ability to detect failures and to take corrective action. The mitigation be implemented at several points in the system. Recovery methods can influence the effects of impact by diverting from populated areas if a failure occurs, or initiating additional mitigation systems that reduce the effects of UAV ground impact.

D.) Reduce the effects of UAV ground impact.

Several factors influence the severity of the UAV ground impact, including UAV mass, size, speed at ground impact, and stored fuel energy. Each parameter has a corresponding lever for reducing the severity of harm created if the vehicle impacts the ground. Limits on UAV size, mass distribution, fuel load, or cruise speed set thresholds on momentum or energy of impact, and therefore act to mitigate the effects of UAV ground impact. Active measures also can reduce the severity of ground impact. Ballistic recovery systems could be used to slow the descent of the vehicle, if an uncontrollable failure occurs and flight termination systems offer the possibility of detonating parts of the vehicle while still in the air to reduce the size, energy, and therefore potential for harm of debris.

There are several factors that must be considered regarding active mitigation measures. They require a control ability to detect and activate in the event of a potential vehicle loss, and could initiate an accident by unintended activation. They must also reduce the energy of impact sufficiently to reduce the severity of the accident's effects. Therefore, they may not be appropriate for larger UAVs that can not be slowed to sufficient speed, or would cause more damage with dispersed debris. Finally, measures such as a flight termination system effectively destroy the aircraft, which results in a complete financial and functional loss of the system.

8.2.2 Possible Mitigation Measures of Midair Collision Risk

A.) Reduce the exposure of risk to other aircraft

As demonstrated in the analysis of Chapter 7, midair collision risk is proportional to traffic density in the area of operation. Although the model did not account for directional effects of traffic flows, they also have an influence on the risk of collision [59]. There are several mitigation measures that can be utilized to reduce the ambient risk of collisions with other aircraft. Similar to ground impact, the measures vary in the degree of separation of UAV traffic from other aircraft.

One strategy is to completely separate UAV operations from other aircraft. This is currently utilized by limiting some military or research operations to restricted airspace. It can also be applied in a more limited form, such as segregating UAV operations to a designated flight level and restricting other operations in the area. A final possibility for separating UAV operations is to conduct them below the height of buildings or structures in the area. For small UAVs, this is a viable strategy to reduce the risk of collision with manned aircraft, as obstructions to navigation are already marked on sectionals and physically visible and most manned aircraft are prohibited from operating within a fixed distance of structures on the ground.

Operational strategies can reduce the ambient risk of operations, while still integrating UAV operations in the NAS. As shown in Chapter 7, collision risk is greatly reduced when operating off airways and off major flight levels. To reduce ambient risk, UAVs could be precluded from operating within airway boundaries, and be required to perform the majority of their mission between major flight levels. Restrictions on airspace and airport operations could also restrict UAVs from operating in airspace classes with increased density.

B.) Reduce the Frequency of Initiating Failures

In the context of midair collision prevention, initiating failures are defined as system or component failures that result in the loss of separation between aircraft. Therefore, mitigation measures in this category assure procedural separation of traffic. That separation fails if aircraft are set on a collision course. Aircraft separation is assured either through procedural or active separation of traffic. Specific implementations of this category of mitigation might be operational or right of way rules or positive separation through air traffic control.

C.) Facilitate Recovery from Failures

Mitigation measures that facilitate recovery from failures prevent collisions if a loss of separation occurs. Facilitating recovery from a potential collision requires awareness of other traffic and control authority for collision prevention. As a collision is the result of the interaction of two or more aircraft, mitigation can be applied to facilitate avoidance by either aircraft. On the UAV, collision avoidance can be achieved through active surveillance and maneuvering to avoid other traffic by capabilities onboard the vehicle or through an external operator. Mitigation measures can also facilitate the avoidance of other aircraft from the UAV. By this strategy, the UAV must be made visible to other air traffic visually, through air traffic control, or by broadcast.

D.) Reduce the severity of UAV mid-air impact

Similar to reducing the energy of ground impact, the risk UAVs pose with respect to midair collisions could also be mitigated by reducing the severity of the impact. The same vehicle design characteristics such as mass, size, and density that influence the magnitude of harm for ground impact also relate to the severity of midair collisions. Additionally, the frangibility, or ease of fracture, of the vehicle influences impact loads. Limiting the UAV characteristics that influence impact loads to certain thresholds could prevent the loss of another aircraft if a collision occurs.

There is a precedent to setting regulatory standards on object impact to not impart substantial damage to aircraft components. Several components of manned aircraft certified under Part 23 and Part 25 are required to continue to function after collision with a bird ranging in weight from 2 to 8 lbs. Additionally, varying limits are placed on construction, mass, and size of kites, balloons, and rockets operated under Part 101.

8.3 Framework for Evaluation of Mitigation

There is a need to evaluate the effectiveness of mitigation measures at reducing or controlling risk. One potential approach to incorporating mitigation measures into the risk analysis is to use an event-based framework similar to the one utilized in Chapter 6 for ground impact. This notional framework is shown below in Figure 32. The framework describes events in an accident sequence and can be applied to a variety of hazards, including ground impact and midair collision depending upon the initial exposure to harm. The event sequence progresses from initial exposure to harm, through a system failure, to adverse effects to the general public. Each node in the tree branches on the potential occurrence of further events in the event sequence, until a final outcome, classified by level of harm, is reached. It should be noted that it was beyond the scope of this thesis to evaluate the effectiveness of specific mitigation measures by this approach.

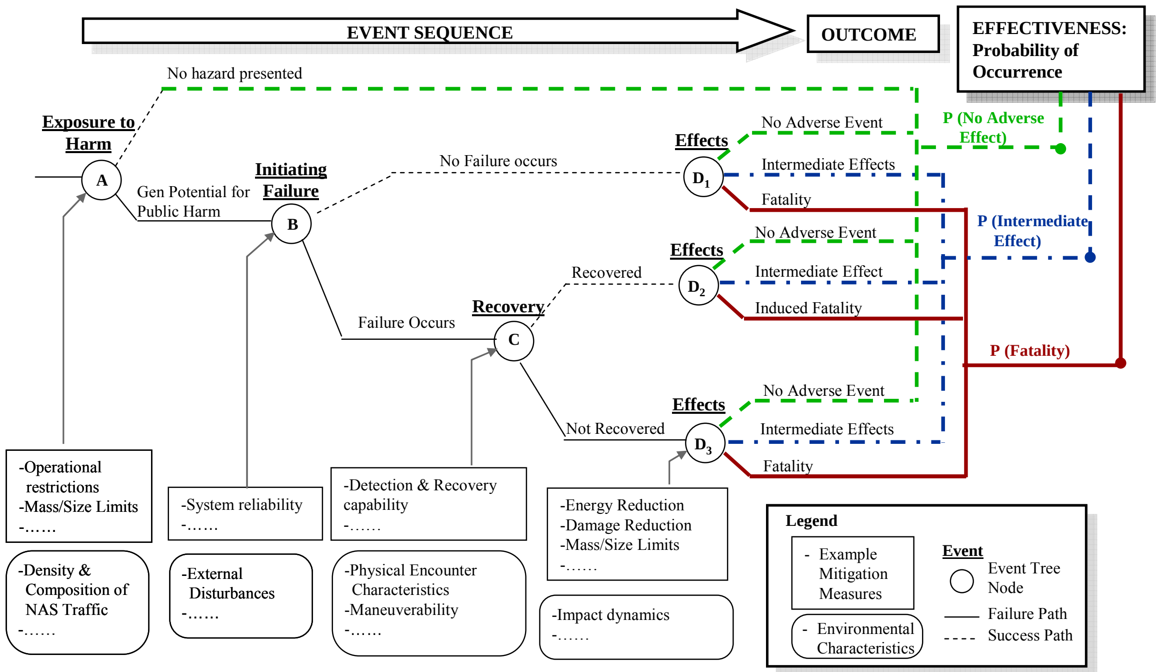


Figure 32: Event Tree-Based Approach to Evaluating Effectiveness of Mitigation

Mitigation measures are separated in the framework by the place in the event sequence in which they have effects, labeled as nodes A through D. The tree terminates in a series of outcomes, shown on the right side of Figure 32. An event node can also be expanded into additional sequences of events to capture the physical dynamics of a specific event sequence. Several example mitigation measures and environmental factors that influence the occurrence of events are shown at the bottom of Figure 32. Some mitigation measures have effects at several points in the event sequence. An example is mass and size limitations, which influence both the likelihood of exposure to harm and the effects of a failure

Each branch of the tree has an associated probability of occurrence conditional on the previous events in the sequence. Coupled with environmental factors, the influence of mitigation measures is modeled by the effect on the conditional probability of each branch. The effects are aggregated through each path in the tree to determine the overall probability of a given outcome, indicated by the total probabilities on the right hand side of Figure 32. In parallel with the evaluation of their effectiveness, the cost, technical feasibility, and policy considerations associated with the implementation of mitigation measures must also be investigated.

One of the limitations of the risk-based analysis is that it does not directly incorporate an analysis of public risk perception. Consideration of the perception of the general public and other operators in the NAS is an important piece of public policy. Research has shown that the public tends to perceive risk based on the benefit they achieve from technology and their opinion of the technology in addition to the quantitative level of risk [62]. Thus, controlling the quantitative level of risk must be considered along with additional mitigation and communication strategies that may be required based on public perception.

8.4 Conclusions

There is a wide range of mitigation measures that can be utilized to reduce the risk of UAV operations in the NAS. The optimal solution for integrating UAV operations into the existing system should utilize the appropriate measures to ensure public safety while maintaining the ability to achieve benefits from UAV operations. An understanding of the cost, feasibility, and effectiveness of the mitigation measures is required so UAV policymakers can incorporate the most effective mitigation measures into the system at the least possible cost.

Chapter 9

Conclusions

Unmanned Aerial Vehicles are emerging as new entrants in the National Airspace System. UAVs can provide a potential public benefit for several applications, yet integration of UAVs into the National Airspace System will be a challenging task. There is a broad range of potential UAV operations, varying by size, performance, and architecture. There is also a broad range of potential policy options for ensuring safe integration.

The FAA has authority over the operation of UAVs and a mandate to ensure public safety in aviation. An approach was taken in this thesis to analyze the various factors that will influence the safe operations of UAVs in the NAS, as well as the regulatory bases and mechanisms for safe operation. A risk analysis for ground impact and midair collision was performed according to FAA system safety standards to compare risk posed by different types of UAV operations and to investigate the influence of vehicle characteristics on risk. Operational and performance characteristics were also examined to determine the safety implications along broad ranges of UAVs.

Military operations have proven the operational concept for UAVs, and provided the impetus behind current efforts in integrating UAVs in the NAS to facilitate operational relocation. Use in civil operations continues to be driven by vital and specialized applications, such as border patrol by the Department of Homeland Security [63]. Several projections indicate that UAVs will be substantial users of the future NAS [2], although the character and type of operations is still uncertain [64]. The routine operation of UAVs will depend upon rules and regulations formed regarding their design, manufacture, and operation

UAV operations can be defined both by the control architecture of the system and by the performance characteristics of different classes. In discussing safety implications, a classification primarily based on mass was adopted. UAVs were classified as Micro, Mini, Tactical, Medium Altitude, High Altitude, or Heavy. The classifications facilitate discussion of the broad range of UAV types and the variation of risk presented to the public.

Preserving the safety of the public is a fundamental requirement in integrating UAVs in the NAS, and is the primary mandate given to the FAA. The FAA has ensured the safety of the current air transportation system through regulation, operational procedures, and technological improvements, but did not anticipate the broad range of emerging UAVs. Current regulations governing unmanned aircraft are limited in scope to balloons, kites, and rockets, and model aircraft. Any UAVs not operated under these rules must be approved by exception granted a Certificate of Authorization to operate in the NAS. The COA application requires lengthy review by FAA officials, and can be inefficient and cumbersome.

To determine the implication of safe integration of UAVs in the NAS, a risk analysis of the critical hazards of midair collision and ground impact was performed according to FAA system safety guidelines. A model of the expected level of safety in terms of ground fatalities and potential collisions was developed based on a model of the physical event sequence resulting in the two hazardous events. The model determined the relationship between operational and vehicle parameters on the risk of ground fatalities and midair collisions. The model did not include potential mitigation or traffic avoidance measures.

The results of the risk analysis show several opportunities for integrating UAVs in the NAS with varying degrees of restrictions. Small UAVs in the Micro and Mini categories can be operated at a relatively low risk to the general public on the ground without significant reliability requirements or mitigation. The risk of midair collisions will have to be mitigated or controlled if it is desired to integrate these classes of UAVs with other traffic in the NAS. Although it was not investigated in this thesis, collision risk may be significantly lower when UAVs of these classes are operated near ground level. Therefore small UAVs may be able to operate in this region without significant collision mitigation.

As the mass of UAVs increases, the risk to the general public also increases significantly. For UAVs in the Tactical, Medium Altitude, and High Altitude classes, additional mitigation will likely be required to protect the general public from harm.

Reliability requirements or operating restrictions may need to be placed on the system to ensure that the risk to the general public on the ground is controlled. UAVs in the Heavy class will require safety levels currently achieved by commercial aircraft to ensure the safety of the general public on the ground. A potential initial operating strategy for this class is introduction into service in oceanic cargo flights, thus limiting exposure of risk to the general public.

Mitigation of midair collision risk is likely to be required for all UAVs that cannot be separated from other air traffic through operational restrictions. The average traffic density in the vicinity of victor airways and jet routes in the NAS is sufficiently high to pose a significant collision risk for all UAV classes without mitigation, under the assumptions of the analysis in this thesis. There are a variety of mitigation measures that can be applied and could vary by UAV mass or type of operation. The ambient risk can be reduced by operating away from regions of high density, as risk was shown to vary by two orders of magnitude between operation on airways and on major flight levels and off major flight and outside of airway boundaries. Therefore, the type of operation of the aircraft will significantly impact the risk.

There is a need to evaluate the impact of mitigation measures on the level of risk posed to the general public and other aircraft in UAV operations. While it was beyond the scope of this thesis to evaluate specific mitigation measures, an event-based framework was introduced that could be utilized to evaluate the effectiveness of risk mitigation measures. The event-based framework can be used to model mitigation measures and environmental characteristics depending upon where the parameters have effect in the event sequence. Consideration of additional factors such as cost and technological feasibility along with mitigation effectiveness can inform a future risk management approach to achieving routine UAV operations in the NAS. The optimal approach will ensure safety through the most effective measures while still enabling public benefit for a variety of operations.

There is a clear demand for the ability to operate UAVs in the NAS, and broad effort to create regulations governing their design, manufacture, and operation. This thesis has systematically examined key UAV operational characteristics relevant to safety, and analytically evaluated two critical risks of ground fatalities and midair collisions. Where analysis indicates that risk levels are unacceptable, a basic framework has been presented to formally evaluate the effectiveness of mitigation measures. The combined analysis presented in this thesis facilitates a thorough understanding of safety considerations for operation of UAVs in the NAS and provides an analytical basis for future regulatory decisions.

Appendix A

UAV Performance Capabilities

Table A1: UAV Performance Capabilities

Vehicle/ Class	Chart Legend	Payload Weight	Max TO Weight	Max Speed	Loiter Speed	Max Climb Rate	Ceiling	Endurance
		(lb)	(lb)	(kt)	(kt)	(ft/min)	(ft)	(hr)
Micro								
Aerovironment Black Widow	Black Widow	0.016	0.133	39	23		800	0.37
Aerovironment Wasp	Wasp		0.4				1000	1.78
BAE Systems Microstar	Microstar	0.033	0.188		80		0	0.33
Mini								
Aerovironment Pointer	Pointer	2	9.6	43	16	300	1000	1.5
Aerovironment/NRL Dragon Eye	Dragon Eye	0.5	5.8	35			1000	0.8
Alcore Azimut	Azimut	4.4	19.8	65	16		985	2.5
EMT Aladin	Aladin		6.6	48			0	0.5
Insitu Seascan/ Scaneagle	Seascan	7.1	33	68	49	492	16000	15
NRL Extender	Extender	7	31	73	39		0	2.3
NRL Sender	Sender	2.5	10	90	50		5000	2
Tactical								
AAI Shadow 200 (RQ-7A)	Shadow 200	55.7	328	123	53	1500	15000	6
AAI/IAI Pioneer (RQ-2A)	Pioneer	100	419	100	80	807	15000	6.5
BAE Systems Phoenix	Phoenix	110.2	397	85	70		8000	4.5
BTA Mini Sheddon	Sheddon		59.5	70	30		12000	2.5
BTA Sheddon Mk 3	Shed Mk3		88.2	70	40		15000	6
EADS SDE Fox AT	Fox	33.1	198.4	97	39		10000	3
EMT Luna	Luna	6.6	66.1	86	26	984	9840	4
General Atomics Prowler II	ProwlerII	100	700	125	50	1500	21000	20
IAI Searcher	Searcher	139	820	105	60		15000	14
Northrop Grumman/IAI Hunter (RQ-5A)	Hunter	250	1600	110	60	761	15000	12
Silver Arrow Mini-V	Mini-V	18	110	110	50	1100	15000	5
Medium Altitude								
EADS SDE Eagle 1	Eagle 1	551	2535	125			25000	30
EADS SDE Eagle 2	Eagle 2	992	7936	240			45000	24
General Atomics Gnat I-Gnat/Rotax 914	Gnat 2	450	1550	160		1300	30000	40
General Atomics Predator (MQ-1)	Predator	450	2250	117	73		25000	40
General Atomics Predator B (MQ-9B)	Predator B	3800	10000	225	70	2400	52000	32
IAI Heron	Heron	551	2425	125	80	650	30000	50
Silver Arrow Hermes 1500	Hermes 1500	661	3637	130	80	902	33000	26
High Altitude								
Aerovironment Centurion	Centurion	600	1400	21			60000	15
Aerovironment Pathfinder Plus	Pathfinder+		700	20			80200	
Aurora Flight Sciences Perseus	Perseus	331	2205	69			65000	27
General Atomics Altus II	Altus II	330	2150	100	65		65000	24
NASA/SCI Raptor Demonstrator 2	Raptor	75	1880	80		5573	65000	48
Northrop Grumman Global Hawk	Global Hawk	2000	25600	395	343		65000	42

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