A FRAMEWORK FOR ANALYZING UNMANNED AIRCRAFT SYSTEM INTEGRATION INTO THE NATIONAL AIRSPACE SYSTEM USING A TARGET LEVEL OF SAFETY APPROACH

A Thesis
Presented to
The Academic Faculty

by

Richard V. Melnyk

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in the
School of Aerospace Engineering

Georgia Institute of Technology
May 2013

A FRAMEWORK FOR ANALYZING UNMANNED AIRCRAFT SYSTEM INTEGRATION INTO THE NATIONAL AIRSPACE SYSTEM USING A TARGET LEVEL OF SAFETY APPROACH

Approved by:

Dr. Daniel Schrage, Advisor
School of Aerospace Engineering
Georgia Institute of Technology

Dr. Hernando Jimenez
School of Aerospace Engineering
Georgia Institute of Technology

Dr. Dimitri Mavris
School of Aerospace Engineering
Georgia Institute of Technology

Mr. Mike Wilson
Southern Regional Office
Federal Aviation Administration

Dr. Vitali Volovoi
School of Aerospace Engineering
Georgia Institute of Technology

Date Approved: 25 January, 2013

ACKNOWLEDGEMENTS

First, I would like to thank my advisor and mentor, Dr. Daniel Schrage. Throughout my time in both the Masters and PhD program at Georgia Tech he has provided me with invaluable mentorship and advice. His long and distinguished career as a Soldier and scholar is certainly one to emulate. I could not have made it through this program without his support.

I also want to recognize the time, support and insight provided by the committee members. Dr. Dimitri Mavris, who despite an extremely busy schedule, always took the time to point me in the right direction and provide guidance on the larger picture of the dissertation process. Dr. Vitali Volovoi and Dr. Hernando Jimenez were always willing to give their time and advice on many aspects of this effort and serve as sounding boards for new ideas. Dr. Jimenez, in particular, provided many hours of his time to serve as a mentor on the dissertation process. I would also like to particularly recognize and thank Mr. Mike Wilson from the FAA's Southern Regional office for volunteering his time and energy and providing insight and feedback into the real-world aspects of this topic.

In addition to the committee members, I want to thank the leadership and staff in the Department of Aerospace Engineering for always being so supportive of us who are simultaneously students and members of the military. Everyone I have dealt with throughout both time periods in the department has been extremely understanding of the unique time constraints we are under.

I would also like to thank Colonel Daisie Boettner, Colonel Grant Crawford and the leadership of the Department of Civil and Mechanical Engineering at West Point. They have not only demonstrated confidence in me by providing this great opportunity, they have allowed me to fulfill the tremendous responsibility of command after this degree and before resuming duties in the department.

I certainly need to thank my fellow graduate students who I spent countless hours with over the last three years working on team projects, preparing presentations, and studying for qualifying exams. I am grateful to have been able to work with such motivated and extremely brilliant people who drove me to push harder and be better.

This is for my parents who early on instilled in me the value of hard work and the attitude to never quit. Finally, I could never have done this without the support of my wife, Cindy. Throughout long work hours, she has always been there for me. To my daughters, Nicole and Ashley, thank you for understanding why Daddy had to spend so much time working on this project for the past year. Anything I accomplish I do to help make a better future for the two of you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	Advisory Circular
ADS-B	Automatic Dependent Surveillance - Broadcast
ALARP	As Low as Reasonable Practicable
ARP	Aerospace Recommended Practice
ASTER	Aviation Safety Targets for Effective Regulation
ATCAC	Air Traffic Control Advisory Committee
AUVSI	Association for Unmanned Vehicle Systems International
CAIB	Columbia Accident Investigation Board
CBP	Customs and Border Protection
CDF	Cumulative Distribution Function
COA	Certificate of Waiver or Authority
CONUS	Continental United States
DHS	Department of Homeland Security
DoD	Department of Defense
DOT	Department of Transportation
EASA	European Aviation Safety Agency
E_c	Expected Casualties
EIA	Environmental Impact Assessment
ELOS	Equivalent Level of Safety
EO	Electro-Optical
ESD	Event Sequence Diagram

ET	Event Tree
ExCOM	Executive Committee
FAA	Federal Aviation Administration
FAFR	Fatal Accident Frequency Rate
FAR	Federal Aviation Regulations
FH	Flight Hour(s)
FHA	Functional Hazard Assessment
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes and Effects Criticality Analysis
FTA	Fault Tree Analysis
GA	General Aviation
GIS	Geographic Information Systems
GWOT	Global War on Terror
HALE	High-Altitude, Long-Endurance
ICAT	International Center for Air Transportation
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
JIPT	Joint Integrated Product Team
JPDO	Joint Planning and Development Office
MALE	Medium-Altitude, Long-Endurance
M & S	Modeling and Simulation
NAS	National Airspace System

NASA	National Aeronautics and Space Administration
NATS	National Air Traffic Services (U.K.)
NHAPS	National Human Activity Pattern Survey
NLR	National Aerospace Laboratory of the Netherlands
NMAC	Near Mid-Air Collision
NTSB	National Transportation Safety Board
OSED	Operational Services and Environmental Definition
PRA	Probabilistic Risk Assessment
RC	Reinforced Concrete
RCC	Range Commander’s Council
RLV	Reusable Launch Vehicle
RTCA	Radio Technical Commission for Aeronautics
SAA	Sense and Avoid
SASO	System Approach to Safety Operations
TBO	Trajectory-Based Operations
TCAS	Traffic Collision Avoidance System
TLS	Target Level of Safety
TOPSIS	Technique for Order of Preference based on Similarity to Ideal Solutions
UAS	Unmanned Aircraft System
UNITE	UAS National Industry Team
VMC	Visual Meteorological Conditions

SUMMARY

There are few who argue the benefits of allowing for greater use of UAS. Despite these benefits, at the time of this research, UAS integration into the National Airspace System (NAS) is extremely limited. This situation is due in some part to technical questions that must be addressed. However, the biggest factor inhibiting a greater degree of UAS integration is concern about public safety. Almost every official statement or document on UAS cites safety as the principal concern for integration. The main premise of this effort is that only when the level of safety required by UAS is articulated, understood and quantified by all sides involved will integration be possible.

Understanding and quantifying risk and safety is not a new field. There are tools available for this analysis already in use with regard to the development and certification of manned aircraft. However, manned aircraft and UAS differ in that one primarily poses risks internally while the other poses them externally. This distinction and the gaps in knowledge caused by this distinction must be addressed in order to fully understand UAS safety.

The purpose of this thesis is threefold. First, it provides a framework to address the problem of being able to address and predict UAS safety. Second, the research analyzes the implications of the ability to predict casualties caused by UAS operations by analyzing several reliability and safety levels. Third and most importantly, the thesis demonstrates how the framework could be used to assist stakeholders in UAS integration efforts.

In the first part of the thesis, a framework was developed to accurately predict casualties caused by UAS operations. Several other studies have examined this problem

and started the process of attempting to quantify the risk to other airspace users and third-party persons on the ground. The main obstacle to quantifying the risk posed by UAS is a lack of understanding of the elements that make up that risk. The framework consists of an overarching approach to the problem, a format to predict UAS risk, and a process that bridges the approach and the format. The overall approach is a Target Level of Safety which uses a goal or target for safety, in the form of a casualty rate, as the basis for regulating UAS. This differs from the failure rate requirements set for manned aircraft in Advisory Circular 1309.

To address the uncertain aspects of this problem, most previous studies have relied on assumptions about the nature of the risk posed to people on the ground in particular with respect to the impact area caused by a UAS mishap, how people are dispersed on the ground, and the level of protection afforded by shelter. A few of the studies focused on ground risk only and did not also analyze the risk of casualties due to midair collisions. None of the studies analyzed the unique risk posed by a loss of data link between the operator and UAS and how those failures impact both the risk of midair collisions and ground impact. Finally, none of the previous studies attempted to validate their models and assumptions using historical data.

Adding more details to the framework as described above accomplished a few things. One, it provides additional confidence in the results because each of the pieces of the model is first shown to originate from a reliable source based on historical data related to the risk posed by UAS. Second, expanding the details of the UAS risk framework and adding a more detailed risk model allows for the analysis of how to effectively mitigate risk. Finally, the framework is shown to be able to accurately predict the casualties caused by aircraft impact by validating the model using manned aircraft accident and casualty data.

In the second part of the thesis, the implications of being able to accurately predict casualties from UAS operations are explored. First, two potential near-term UAS applications are explored. Second, manned aircraft failure rate standards from AC 25.1309 are applied to different UAS applications. The intent is to determine if applying manned reliability standards to UAS is appropriate. From these experiments it is determined that applying manned aircraft failure rates to UAS would indirectly require UAS to be anywhere from one to ten orders of magnitude safer than current manned aircraft operations. Finally, various potential safety level values are implemented to determine the impact on possible UAS operations. Based on the results, mandating safety levels more stringent than current manned fatality rates would eliminate nearly 40% or more of possible UAS and environment combinations.

In the third part of the thesis, the use of the entire framework is demonstrated for three case studies. In addition, the models from the framework are utilized to demonstrate how the TLS approach could be used to develop certification requirements for both the UAS and potential mitigation measures. Perhaps the most important aspect of this part is the development of maximum failure rates for specified combinations of UAS categories and operating environments. What is particularly important about these results is that the allowable failure rates to meet a specified TLS value can vary by as much as ten orders of magnitude. Finally, the framework is utilized to determine minimum sense and avoid effectiveness levels for the various, proposed UAS categories in the different classes of airspace. The results of these experiments show that some combinations of UAS and airspace class do not require sense and avoid technology to meet the specified target level of safety while other combinations require a system with up to 99% effectiveness.

INTRODUCTION

" Some pilots said the problem could never be solved—that flying would depend on men with the skill of flying by instinct."

- James Doolittle on the challenges of instrument flying.

Throughout our history technological advances have changed our lives. Some changes are incremental improvements and others are more fundamental in nature. Those changes that are more fundamental in nature are often embraced reluctantly, especially when there is a question of whether their benefits outweigh their risk. The modern advent of Unmanned Aircraft Systems (UAS) is arguably one of the most significant and revolutionary changes in aviation history and ranks in importance along with the first manned flight, the use of instruments to fly without visual reference to the horizon, and the introduction of the jet engine.

However, not all of these breakthroughs share the same characteristics. Conquering heavier than air flight and the introduction of jet engines were both primarily technological breakthroughs. Instrument flying, on the other hand, was a different type of problem. In addition to requiring technological breakthroughs, flying without visual references required fundamental changes in the procedural, regulatory and operational nature of flight. As a result, it required a more comprehensive solution. The integration of UAS into the NAS represent just such a change to the aerospace industry and society as a whole.

There is no question that UAS have offered and can continue to provide tremendous benefits. They are relatively cheap to operate, can be simple to maintain and most importantly, can perform missions without putting a pilot in harm's way. Normally, removing a human from a machine is considered a safety benefit. For example, few would prefer to send an ordinance disposal technician in to defuse a bomb when a robot could accomplish the task.

Unlike that example, removing the human from an aircraft can create risk as well as reduce it. Perhaps even more troubling is the fact that an unmanned aircraft removes risk from a willing individual, in the form of the pilot who now becomes a remote operator, and potentially places that risk on second and third-party individuals in the form of other airspace users and bystanders on the ground.

The military has already demonstrated that UAS can operate alongside manned aircraft in places like Iraq, Afghanistan and in limited areas in the United States. While some technological hurdles remain before complete integration can be achieved in the NAS, the fundamental question that needs to be answered is how to integrate UAS safely. The goals of this thesis were to continue the dialogue on safety and to propose a framework to openly and objectively determine how safe is safe enough, estimate how safe unmanned aircraft would be if integrated into the airspace now, and finally shape how stakeholders evaluate competing or even complementary measures to ensure UAS meet required safety targets.

This academic effort certainly could not solve the problem of UAS integration. In fact, this research purposely avoided proposing any specific technology or procedure designed to support UAS integration. There are already many groups working on these particular problems. It was more important, in the opinion of the author, to establish an understanding of what metrics must be set for safe integration to take place so that all of the various efforts already underway in this process will fit into a common goal. The National Aerospace Research and Development plan identified the lack of integration metrics as a primary reason for lack of progress on this problem [1]. Without a common goal, no single group or entity is able to determine when unmanned air vehicles will be ready to share the skies with their manned counterparts.

This document outlines why this problem is relevant, discusses the root of the problem that needs to be addressed, and outlines the steps the author conducted to address the problem of analyzing safe UAS integration. In the Background section, the paper briefly covers the history of UAS, past efforts toward UAS integration, discusses current and proposed UAS classification systems and defines several important terms related to reliability and safety. The section on Relevance outlines why UAS integration is important to the United States from a military, public, and civil point of view. The section titled Defining the Problem covers the challenges associated with UAS integration and why this is a problem that needs to be addressed. In particular, this section focuses on Safety and why this is an overarching challenge for UAS integration. The Literature Review section identifies recent attempts to address the problem of integration and identifies studies from other areas that offer additional insight into addressing the integration challenges. The Research section outlines the research objectives and questions associated with the thesis, and offers hypotheses that the research attempted to answer. In the Results and Discussion section the author discusses the methodology and data sources used in this research as well as details the results of the framework and demonstrates how it can be used in the future for integration efforts. In the Conclusions section, the paper reviews the major findings of the research as well as the contributions of this research. Finally, in the section on Future Work, the author highlights several areas that require further research to better understand the problem and recommends areas of interest for the six proposed UAS test centers.

BACKGROUND

History of UAS

Unmanned Aircraft Systems or UAS are not a new phenomenon. In fact, unmanned aircraft were used in the United States as early as the Civil War. During that conflict an unmanned balloon was equipped with explosives set to drop based on a timing device so that the vehicle could deliver bombs over enemy positions [2]. Japan attempted a similar tactic during World War II but failed to achieve any tactical success [3]. The fact that the same concept was unsuccessfully attempted 80 years after the Civil War shows that the technology required to operate UAS had not advanced considerably during that time. This is in contrast to the rapid advances made in manned aviation during that same time period which ushered in the jet age. Germany's use of the V-1 and V-2 'buzz bombs' during World War II technically qualifies as an unmanned aircraft although their employment more closely resembles what we now consider cruise or ballistic missiles.

It was during the Vietnam conflict that the U.S. began using unmanned aircraft for surveillance that most closely resemble the UAS that are more prevalent today. The AQM-34 Firebee, pictured in Figure 1, was used extensively throughout Southeast Asia during that conflict and even employed a limited amount of stealth technology to avoid detection [2]. It is during this period that the term 'drone' was adopted, a misleading term which is still common in the media to this day when referring to UAS [3].

Figure 1: AQM-34 Firebee [2]

In the period after Vietnam up to the more recent Global War on Terror (GWOT), the Israelis contributed the most to UAS advances. Their designs were the basis for the only two major UAS designs the U.S. operated during Operation Desert Shield / Storm; the Pioneer and the Hunter [3]. However, it was not until the more than decade long conflicts in Iraq and Afghanistan that the right combination of technology, operational needs and permissive operating environment existed to drive the exponential growth in UAS utilization and sophistication.

Never before in history have unmanned systems been used to the extent they have during the GWOT. For example, Figure 2 shows the major UAS programs of record for the Department of Defense from 1985, projected out to 2030. While not all-inclusive, it shows that in 1995 only two major systems existed, the aforementioned Pioneer and Hunter. Presently, the number is many times that and is projected to increase even more over the next 5-10 years. This increase in UAS usage by the DoD will be discussed in more detail in the Relevance section below.

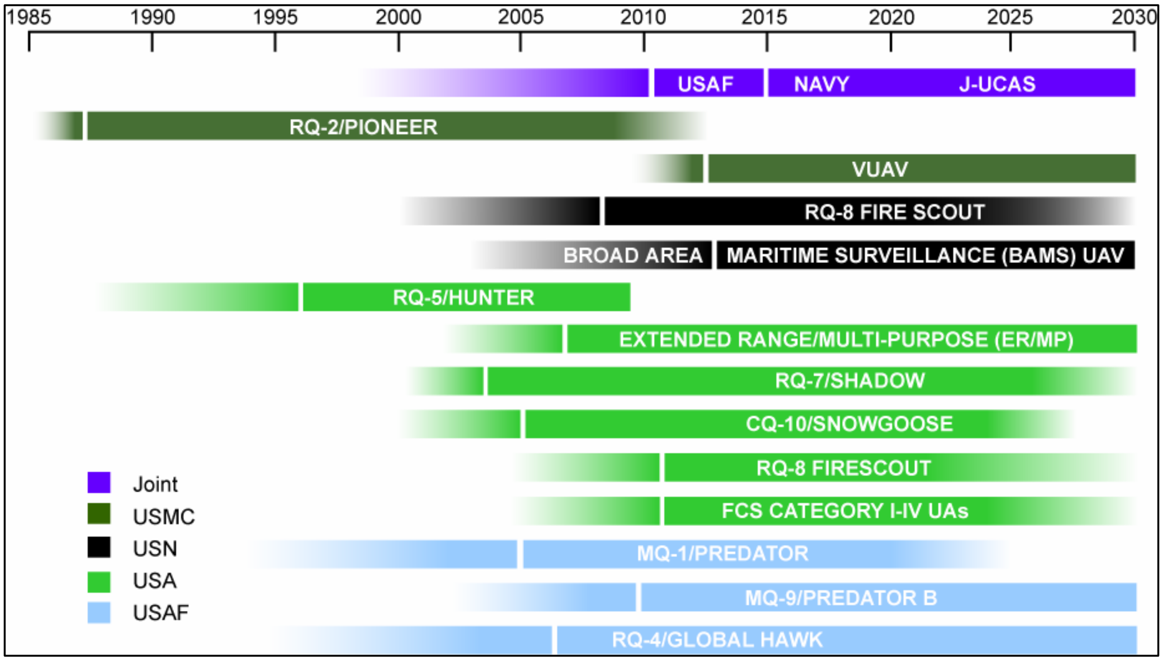


Figure 2: DoD UAS Programs from 1985 projected to 2030 [4]

History of UAS Integration Efforts

While UAS themselves are not new to the aviation community, coordinated efforts to understand and accomplish integration into the NAS are relatively new. As the history of UAS section alludes to, UAS have been confined typically to use on the battlefield. The purpose of this section is not to provide an exhaustive history of UAS integration but to provide a short background describing what agencies or organizations have been involved in this process in the past or continue to play a role in UAS integration efforts at the current time.

In 2003, a law signed by President Bush mandated the creation of the Joint Planning and Development Office (JPDO) within the FAA to plan and coordinate the efforts toward the creation of the NextGen air transportation system [5]. Unmanned

Aerial Vehicles (UAVs), as they were addressed at the time, received little mention and only as one of many types of aircraft operations that NextGen was intended to integrate. Overall, the JPDO was responsible for developing a research and development plan but not given full authority over UAS integration. Over the next several years, several other organizations tried to manage UAS integration into the NAS.

Cropsey [6] provides a thorough description of the UAS integration attempts that occurred from the earliest organized efforts in 2004 until 2008. The first such effort was called Access 5, which started in 2004 under the National Aeronautics and Space Administration (NASA). It consisted of elements from the Department of Defense (DoD), NASA, the Department of Homeland Security (DHS), the Federal Aviation Administration (FAA) and a group of industry partners collectively known as UNITE, for UAV National Industry Team. The work of Access 5 was focused on the idea of gaining access to the NAS by larger, high altitude UAS referred to as HALE. The HALE classification will be discussed in the following section but stands for High-Altitude, Long-Endurance. The Access 5 concept assembled some of the most important stakeholders in this process together in one organization. However, it lost the funding from NASA in 2006 due to cutbacks in that organization's budget and did not survive after that.

The FAA created a special advisory committee under RTCA (Radio Technical Commission for Aeronautics) to study UAS integration and recommend standards for their operation in 2004. This special committee, referred to as SC-203, remains active at the time of the writing of this document and has published two major documents to date

[7]. The first one, titled *DO-324,* Guidance Material and Considerations for Unmanned Aircraft Systems, was published in 2007 and the second *DO-320,* Operational Services and Environmental Definition (OSED) for UAS, was published in 2010. The committee was scheduled to publish another document at the end of 2012 and two in 2013. The purpose of the first document was to establish common definitions of key terms and the second document provided an analysis of the functions and performance characteristics of UAS and the corresponding elements of the NAS [8]. This committee's future documents are expected to establish performance standards for UAS, including the Sense and Avoid (SAA) systems.

Seeing the need for expanded access to the NAS for training and testing purposes, the three main services in the DoD formed a Joint Integrated Product Team (JIPT) to look at UAS integration. The group, formed in 2005, was an ad-hoc organization that came together informally and attempted to define the scope and requirements for the integration problem. Again, funding became an issue and without formalizing and expanding the organization, the JIPT was not able to make any significant progress. However, the visibility gained by their effort led to the formation of another group at the Secretary of Defense level [6].

It was around the time that all of the previous efforts to develop integration plans were faltering, that Congress became more involved. Concerned about the lack of progress, the National Defense Authorization Act signed in 2008 and implemented in 2009 called for the creation of an Executive Committee (ExCOM) with representatives from both the Department of Transportation (DOT) and the DoD. The committee eventually included NASA and the DHS as well [9]. The formation of the ExCOM marked the first time that several important stakeholders came together to look at this problem based on a formal requirement from Congress and linked to funding as opposed to the more voluntary organizations formed in the past. However, unlike the Access 5 effort, the ExCOM did not originally include representatives from industry.

The Executive Committee report on integration, published in 2010, recognized four broad classes of challenges to UAS integration which included Regulatory, Operational and Procedural, Technology, and Standards challenges [9]. Later in the Motivation section of this paper, these broad categories will be combined into the two major categories of Regulatory and Standards, or Operational and Technological. The major distinction between the two is that the Operational and Technological category primarily deals with either actual components of the UAS, or how UAS are operated. On the other hand, the Regulatory and Standards category deals primarily with rule-making and enforcement. The ExCOM had four stated goals which were largely to coordinate efforts among the involved agencies [9]:

Goal 1. Coordinate and align efforts among key Federal Government agencies (FAA, DoD, DHS, and NASA) to ultimately achieve routine safe federal public UAS operations in the National Airspace System.

Goal 2. Coordinate and prioritize technical, procedural, regulatory, and policy solutions needed to deliver incremental capabilities.

Goal 3. Develop a plan to accommodate the larger stakeholder community, at the appropriate time.

Goal 4. Resolve conflicts among Federal Government agencies (FAA, DoD, DHS, and NASA), related to the above goals.

There were two major results that came out of the ExCOM process. First, they identified the recommended timeline for UAS integration as 2015 and also stipulated the requirement for six test centers throughout the US for expanded UAS capability testing. In addition, the DoD identified six different levels or types of access to the NAS in an effort to expand integration incrementally instead of an all or none approach [9].

A key statement that was published in the 2010 report on integration that is critical to this research is the recommendation to use a Target Level of Safety (TLS) approach to set safety goals for UAS operations. This approach and other similar recommendations to use this approach will be addressed again when discussing the approach used in this thesis. Although the ExCOM recommendations were specific and incremental, there was still no requirement to act. In addition, no entity was designated as a lead agent in the process so there was no single agency or person with overall responsibility for UAS integration.

Around this time the Office of Management and Budget also required the JPDO to publish a report on the Research and Development requirements for UAS integration by late 2011. This document was originally published in early 2012 and consisted of a roadmap of UAS research challenges and goals [10].

Once again frustrated at the lack of progress with UAS integration efforts and likely pushed by UAS manufacturers for signs of movement, Congress passed and the President signed a bill into law in February of 2012 that directly addressed UAS integration. The contents and details of this bill will be discussed in more detail in the section titled Legal Mandate, but the important result of this law was that now UAS authorization was a requirement tied directly to funding for the FAA. Shortly after the passing of this law, the FAA established a single office within the agency with responsibility for UAS integration in March of 2012 [11].

Some of the key aspects of this law that changed the integration dynamic are that it specifically directed the Secretary of Transportation to develop an integration plan and to consult users and industry on the plan. It also directed the Secretary to "carry out all safety studies necessary to support the integration of unmanned aircraft systems into the national airspace system" [12]. The law states that if the Secretary determines that UAS are safe to operate in the NAS based on characteristics such as size, location, etc. then the UAS will be allowed to operate in the NAS. Of course, a key part of this requirement that will be addressed throughout this thesis is the definition of 'safe to operate'.

At the time of writing this document, one of the first key requirements in the 2012 law passed is already behind schedule. The requirement to name six test centers to advance UAS integration has not been met. The FAA cited concerns over privacy in announcing the delay, although privacy is typically not a concern of the administration [13].

UAS Classification Systems

After gaining a better understanding of the history of UAS, it is also important to understand the current state of UAS and how they are classified or categorized today. The concept of categorization or classification will be revisited in the section on

Applications to Certification in Part 3 of the Results and Discussion section of this paper. Unfortunately, there is not one standard classification system for UAS as there are commonly accepted definitions of manned aircraft. The only reason for the discussion of UAS categories or classifications at this time is to point out the current lack of agreement on any such convention. It is the author's belief that the omission in this area reflects the lack of consensus among stakeholders about the way to regulate UAS, and the fact that the growth of types and uses for UAS was a phenomenon driven primarily by unexpected conflicts. In other words, the proliferation of UAS technology and applications happened so quickly and primarily in the military domain that regulations have not maintained pace.

Department of Defense Categories

The U.S. Department of Defense, by far the most prolific UAS operator, classifies UAS into groups based on operating weight and capability. These group breakdowns appear in Figure 3. They range from the extremely small Group 1 UAS, represented by the hand-launched Raven, to the extremely large and complex Group 5 UAS characterized by the Global Hawk system. This classification system focuses primarily on the physical and performance characteristics of the system, in terms of weight and speed, with a secondary consideration toward the environment in terms of operating altitude. This system has become the accepted one within the DoD.

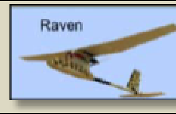
UAS Groups	Maximum Weight (lbs) (MGTOW)	Normal Operating Altitude (ft)	Speed (kts)	Representative UAS	
Group 1	0 – 20	<1200 AGL	100	Raven (RQ-11), WASP	
Group 2	21 – 55	<3500 AGL	< 250	ScanEagle	
Group 3	< 1320	< FL 180		Shadow (RQ-7B), Tier II / STUAS	
Group 4	>1320		Any Airspeed	Fire Scout (MQ-8B, RQ-8B), Predator (MQ-1A/B), Sky Warrior ERMP (MQ-1C)	
Group 5		> FL 180		Reaper (MQ-9A), Global Hawk (RQ-4), BAMS (RQ-4N)	

Figure 3: U.S. DoD Unmanned Aerial System Group Classifications [14]

Other Categories

Another classification system that appears throughout the literature because of its widespread use for many years is one that primarily focuses on the planned operating environment and mission for the vehicle. The two primary categories in this system are HALE and MALE or High-Altitude, Long-Endurance, and Medium-Altitude, Long-Endurance. The generally accepted breakdown for these categories is above 30,000 ft operating altitude and an indefinite range for HALE, and below 30,000 ft and a range of over 200km for MALE [15]. These classifications were used in an important study on UAS safety and integration from the Massachusetts Institute of Technology. The study will be discussed in more detail below in the section on the Literature Review.

FAA Categories

The Federal Aviation Administration does not have an official UAS grouping or classification system, but there are some differences in their regulations that could lend itself to a categorization or even certification process. Currently, the FAA differentiates UAS primarily by the user and the intended use. The path to being allowed to operate in the NAS is different if the operator is a public entity, commercial entity, or recreational or hobby operator. The authorization process for public entities will be discussed in more detail later, but the one main UAS characteristic used to distinguish between UAS for the FAA exists in the model category. Unmanned aircraft not operated by public or commercial entities that adhere to certain guidelines can operate under Advisory Circular (AC) 91-57 [16]. This one page document allows model aircraft to operate no higher than 400 feet, operate within line of sight of the operator, and must avoid populated areas or noise sensitive areas. Contact with controllers must be established prior to operating within three miles of an airport and the right of way always remains with actual aircraft [17]. What is interesting about this policy is it begins to address the operating environment of the vehicle, for what one would assume to be both noise and safety concerns. The idea of considering the environment as a certification concern for safety will be discussed later during the portion on the overall approach of this work.

A newer standard from the FAA does not create categories of UAS, but does differentiate air vehicles by weight. A bill signed into law in February of 2012 mandates certain timelines for UAS integration. Two particular timelines that stand out are the requirement to allow flight of 'very small UAS' or those that weigh 4.4 lbs or less to fly within 90 days of signing and the requirement to allow 'small UAS' or those that weigh

55 lbs or less to fly within 270 days [12]. Clearly this law creates differentiation of UAS by weight while remaining short of actually establishing a UAS category. These two particular weight cutoffs will be analyzed in more detail later in this document.

Foreign Categories

Yet another classification system based in Europe appears below in Figure 4. This system actually seems to alternate its criteria between size (Nano, Micro, Mini) then range (Close, Short, Medium) and then altitude and endurance. An important distinction in the European system currently occurs at 150kg (approx. 330 lbs). The European agency responsible for certifying aircraft actually exempts UAS below this weight from their typical certification standards and allows any airworthiness standards to be handled by the individual nation [18].

UAS Categories	Acronym	Range (km)	Flight Altitude (m)	Endurance (hours)	MTOW (kg)	Currently Flying
Tactical						
Nano	η	< 1	100	< 1	< 0,025	yes
Micro	μ (Micro)	< 10	250	1	< 5	yes
Mini	Mini	< 10	150 [b] to 300 [a]	< 2	< 30 (150 [b])	yes
Close Range	CR	10 to 30	3.000	2 to 4	150	yes
Short Range	SR	30 to 70	3.000	3 to 6	200	yes
Medium Range	MR	70 to 200	5.000	6 to 10	1.250	yes
Medium Range Endurance	MRE	> 500	8.000	10 to 18	1.250	yes
Low Altitude Deep Penetration	LADP	> 250	50 to 9.000	0,5 to 1	350	yes
Low Altitude Long Endurance	LALE	> 500	3.000	> 24	< 30	yes
Medium Altitude Long Endurance	MALE	> 500	14.000	24 to 48	1.500	yes
Strategic						
High Altitude Long Endurance	HALE	> 2000	20.000	24 to 48	(4.500 [c])12.000	yes
Special Purpose						
Unmanned Combat Aerial Vehicle	UCAV	approx. 1500	10.000	approx. 2	10.000	yes
Lethal	LETH	300	4.000	3 to 4	250	yes
Decoy	DEC	0 to 500	5.000	< 4	250	yes
Stratospheric	STRATO	> 2000	>20.000 & <30.000	> 48	TBD	no
Exo-stratospheric	EXO	TBD	> 30.000	TBD	TBD	no
Space	SPACE	TBD	TBD	TBD	TBD	no

TBD = To Be Defined [a] = according to national legislation [b] = in Japan [c] = Predator B

Figure 4: European UAS Classification System [19]

Manned Aircraft Categories

It is also noteworthy to examine how the FAA certifies manned aircraft before looking too deeply into UAS in order to be able to make a comparison later. Focusing on the most prevalent aircraft, the FAA broadly divides aircraft into rotorcraft and all others. Looking at fixed-wing aircraft, the main categories are Normal, Utility, Acrobatic, and Commuter under Federal Aviation Regulation (FAR) Part 23 and Transport aircraft under Part 25. Rotorcraft have a similar distinction between Normal and Transport under Parts 27 and 29, respectively. It is evident that Transport aircraft are held to certification requirements different enough that they warrant a completely different set of standards.

What differentiates aircraft between these major categories amounts primarily to intended use but is manifested in differences in propulsion, weight, and number of seats [20]. The characteristics can be correlated to the capacity to injure occupants based on the amount of people an aircraft can expect to carry and whether the role of the aircraft is to carry passengers for hire.

Risk, Reliability and Safety

As will be discussed later, the fundamental problem inhibiting UAS integration is safety-related. Therefore, it is important to first define safety in the context of integration and compare safety to risk and reliability. All three terms are closely related and each will have a part in this thesis. However, a review of the concerns from stakeholders involved in UAS integration clearly indicates that safety is the main requirement for integration. Before discussing these areas further, it is instructive to have a basic definition of what these terms mean since their meanings can sometimes differ depending on the source and application.

Reliability generally refers to the probability that an item or system will "perform a required function, under stated conditions, for a stated period of time" [21, 22]. In essence, it refers directly to whether an item will fail to perform in its intended way. A lack of reliability, however, does not necessarily mean that the system will be unsafe. For example, a component on a sunken ship that resides on the bottom of the Atlantic Ocean is probably not very reliable. However, given its current location it does not pose a risk to society, unless it is leaking a hazardous material.

Risk combines the probability or likelihood of an event and the consequences of that occurrence [23]. A typical risk matrix appears in Figure 5 and demonstrates how risk is a combination of both the likelihood of an incident and the consequence or severity of that incident. Risk is the inverse of safety so any understanding of safety must also take the probability and consequences of a hazard into account.

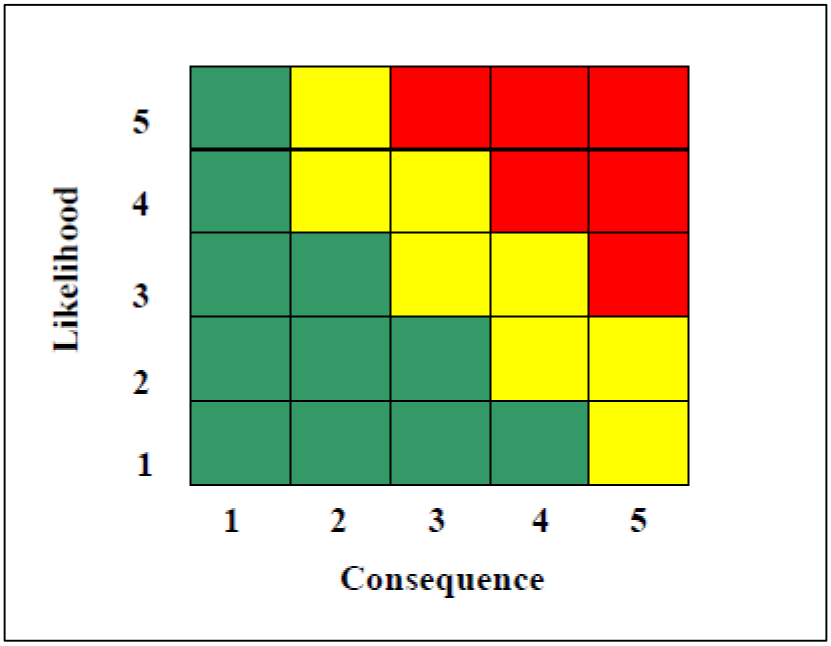


Figure 5: Generic Risk Matrix [24]

Oddly enough, the standard used to conduct safety assessments of civil aircraft does not include the word 'Safety' in its list of definitions [22]. This document defines hazards as "A potentially unsafe condition resulting from failures, malfunctions, external events, errors or a combination thereof", but provides no direct definition of safety. Of course since safety is the major concern of stakeholders, it is important to understand this concept before moving forward on this problem.

The FAA's System Approach to Safety Operations (SASO) website's glossary of terms does not include a stand-alone definition of safety. There is a term for System Safety, which is defined as "system safety aims to identify, analyze, assess and control hazards and risks associated with a complete system" [25]. The FAA's order on the Safety Management System explicitly defines safety as "The state in which the risk of harm to persons or property damage is reduced to and maintained at or below an acceptable level through a continuing process of hazard identification and risk management" [26].

Based on these definitions we can develop an overall concept to operate under. Hazards are those conditions that can cause harm. They can be internal or external. Reliability refers simply to the likelihood that a hazard due to system failure will occur. Risk is therefore a combination of the severity of those hazards and the likelihood that the hazards will occur. Safe conditions exist when the risks are below an acceptable level. This is the basic definition of safety that will be used in this document. Referring back to Figure 5, a condition of safety occurs in the green boxes in the lower left portion of the figure. An unsafe condition exists when the boxes are red and the yellow boxes indicate marginal safety.

In the context of risk and this research it is also important to distinguish between Collective and Individual Risk. The Department of Defense's Range Commander's Council (RCC), which handles a variety of missile, rocket, laser, explosives and artillery testing for the government, defines each term. Individual risk is the measure of risk to an individual person and is quantified by the probability that the person will become a casualty (P_c) due to all the hazards present [27]. Collective risk, on the other hand, focuses on the expected number of casualties (E_c) across a defined group based on the hazards presented [27]. This number can be quantified on an annual, per mission, or any other time-related basis. This term is sometimes also referred to as Societal risk. Later in this thesis the analysis will focus on collective risk and the E_c per flight hour or a specified number of flight hours. The reason why the research will focus on collective risk is two-fold. One, the purpose is to understand UAS integration from an overall or statistical perspective and not focus on one particular area or operating environment. Two, focusing on collective risk enables a comparison of UAS risk with risk values already associated with manned flight, which are tracked as accidents or casualties per flight hour (FH), 100,000 flight hours or 1,000,000 flight hours typically.

Current State of Certification and Safety Methods

The following section will detail how UAS are currently allowed access to the NAS and contrasts the current process for UAS with the certification process for manned aircraft as well as the risk assessment process for other applications. UAS have limited access to the NAS via two different paths, depending on whether the user is a public or civil entity. The section will also go into some detail about the certification process for manned aircraft and contrast some of the attributes of that process with the needs of UAS certification procedures. Finally, this section examines risk assessment processes for other applications that share certain characteristics with UAS operations to gain insight into potential certification or risk analysis procedures.

Certificate of Authorization or Waiver

As of April 2012 the FAA listed 61 sponsors who had permission to operate UAS in the NAS by means of a Certificate of Authorization or Waiver, also known as a COA. This option is only available to public operators, thus the list is dominated by the military, law enforcement and some academic organizations [28]. The FAA's website now features an online process to obtain the COA and states that a formal reply will occur within 60 days of receipt of the application [29]. In the past, the process took up to six months to complete. The FAA also increased the time that the COA is valid from 12 to 24 months to decrease the frequency that users must update their COAs and also added a process for an expedited COA in the case of disaster response or emergencies [11]. So, while there has been a concerted effort to streamline the COA process, the example application that the website features indicates that the application is a very detailed document that includes specific information about the equipment being used by the system, the way in which it will be operated, and features an emphasis on lost link and emergency procedures. Obviously, this is nothing like the basic 'file and fly' procedures under which pilots operate.

The COA process is cumbersome and is not adequate in the long term to satisfy the training and testing requirements projected for military unmanned systems [14]. The major drawback of the COA system is that each waiver is specific to the airframe, user, location and proposed mission in question. If there are any major changes to any of the aspects of the COA, the approval process must be restarted. At a minimum, the COA must be reviewed annually. Thus the approval process can be lengthy, is resource intensive and not very flexible after the document has been approved. The DoD specifically addressed the COA process in their latest Unmanned System Integration plan and stated that the “process is adequate for enabling a small number of flights, but does not provide the level of airspace access necessary to accomplish the wide range of missions at current and projected operational tempos (OPTEMPOs)” [30].

Due to the lack of inherent ‘See and Avoid’ or ‘Sense and Avoid’ capabilities in UAS, the COA process also requires that the operator remain within line of sight of the air vehicle or that an air or ground spotter maintain visual contact with the UAS and radio contact with the operator. An article describing the use of a UAS for remote sensing related to natural resources describes additional impediments to operating under a COA. Because of the requirement to have ground observers view the vehicle at all times, the team that operates the UAS must employ many more people than should be necessary or operate within an extremely small distance from the ground controller [31]. Clearly, the COA process is does not adequately accommodate current and future DoD usage as well as any desired civil UAS usage.

Experimental Airworthiness Certificate

Civil entities cannot utilize the COA process and must instead apply for and receive certification of their UAS under an experimental category using FAA Order 8130.34 [29]. This order specifically limits the operation of UAS under this category to research and development, operator training, and market surveys [32]. For UAS users who are not considered public, the FAA has published interim airworthiness guidance [33]. Essentially, the interim guidance document states that UAS must “be in a condition for safe operation”. In addition, it states that to the degree possible, UAS users will adopt the certification standards used by similar manned aircraft. The disadvantages of using this approach will be discussed in more detail below.

However, even if the COA process was expanded to allow Civil UAS users to take advantage of the process, it would not satisfy many of the stakeholder requirements discussed above. First, the process does not allow for routine and efficient access to the NAS because of the restrictions already outlined. Perhaps more importantly, the COA is a procedural document. An applicant for a COA must describe specific procedures that the user will follow and describe particular events such as a lost link failure. There is no provision within the COA process for an actual assessment of a quantifiable safety level, nor is there an upper, quantifiable limit on how risky an operation can be. Because the current users of COAs operate in fairly narrow areas under restricted operations and with limited integration with other airspace users, the COA process tries to achieve safety through procedures, checklists, and isolating the hazards from other airspace users or bystanders on the ground. However, this process does not approach achieving full integration, nor does it allow stakeholders to assess the level of risk posed by UAS operations.

Manned System Safety and Risk Assessment

Safety and Risk Assessment at the development stage is handled as part of the certification process for new manned aircraft. Unlike UAS developers, stakeholders for manned aviation are primarily concerned with the safety of the aircraft occupants. For example, Aerospace Recommended Practice (ARP) 4761, which serves as a guide for the safety assessment process, states that the assurance or reliability level for an aircraft "depends on the severity of the effects of failures or development errors of that function on the aircraft, crew, or occupants" [34].

Another document relevant to aircraft safety assessments, ARP 4754, does mention that the certification process for aircraft should take the operating environment of the aircraft into account, but an examination of the language in that requirement reveals that the concern is for the aircraft itself. For example, the environmental considerations should include "atmospheric, electromagnetic, lighting conditions; and hazardous objects and materials", while the operational assumptions should include "exposure times, traffic densities, maintenance intervals and performance limitations" [35]. With the possible exception of traffic densities, nothing in this list indicates that the certification process accounts for an aircraft's effects on bystanders. Not only does this approach make it more difficult to apply to UAS, it would potentially penalize UAS operators by not allowing them to use the environment as another aspect of safety. In other words, if a manned aircraft designer identifies and assesses an unacceptable risk, the designer must design something into the system to mitigate that risk. Designers of UAS, on the other hand, could use the environment as a mitigating technique if they choose to purposely restrict UAS operations to areas that pose less risk to bystanders.

The other aspect of the safety assurance process for manned aviation involves the certification of components that are incorporated into aircraft. The Code of Federal Regulations dealing with aviation has extensive certification standards for components that are going to be used on aircraft that cover almost any possible sub-system or component. This is possible because manned aircraft have remained relatively unchanged over time and there is a sufficient amount of data to prove the safety levels of manned aircraft. Therefore, the assumption is that if aircraft have already achieved a certain level of safety using these certification standards, then future aircraft that apply the same standards should also achieve a certain safety level.

If a designer or manufacturer wishes to develop a new component or sub-system, the designer must demonstrate that it meets an Equivalent Level of Safety (ELOS) to the one it replaces [36]. Unfortunately, there are three obstacles to implementing the same ELOS and certification approach that manned aircraft use for UAS. First, UAS do not and will not necessarily resemble and operate like their manned counterparts. For example, some fixed-wing UAS do not require runways but instead use catapults for launch. UAS can be much smaller than manned aircraft and therefore have different structural and safety requirements. An article comparing structural requirements for manned aircraft to several different UAS indicates that achieving manned aircraft standards may be difficult or unachievable for current UAS [37]. Second, UAS are evolving so quickly, compared to manned aircraft, that it may be difficult to maintain a set of certification standards applicable to emerging designs. Third, and perhaps most important, UAS operations do not yet have the necessary data to build the certification standards required.

Examples of Other Safety or Risk Assessment Methods

While there are many different safety assurance or risk assessment methods that could be discussed, two in particular merit attention because of their potential application to this effort. The Range Commander's Council (RCC) is a joint Department of Defense (DoD) entity responsible for developing acceptable risk criteria and risk assessment analysis techniques for DoD activities that include hazards such as explosives, rocket launches, and missile launches [27]. They do this by establishing acceptable risk criteria, which is similar to a Target Level of Safety, which will be discussed in more detail later in this document. They then establish methods to assess the risk of an operation such as a missile launch and implement mitigation measures, if necessary, to reduce the risk to an acceptable level. The applications for these methods are analogous to UAS operations because the hazards posed by UAS are similar to a rocket or missile launch in that the hazards are primarily to bystanders and not to occupants on the system in question. In other words, unlike the manned aircraft safety process, the RCC is concerned with risks caused by the system to those outside the system.

The RCC already published a document that outlines the risk assessment and mitigation process for UAS [38, 39]. However, due to the current nature of UAS operations for the DoD, the document is primarily concerned with containment of UAS risk and avoiding operations over population or near other airspace users. There is some discussion in the supplement on casualty assessment techniques, but the document is not definitive in how to accurately assess the risk posed by UAS operations in a fully integrated manner. However, the overall RCC concept of setting acceptable risk criteria and then measuring whether an operation meets those criteria is very useful for this thesis.

The Nuclear Regulatory Commission (NRC) and the Department of Energy also use a threshold for risk criteria similar to a Target Level of Safety in its applications. The industry uses event and fault trees, which will be discussed in greater detail later, to determine the probability of certain events occurring. They then assess the hazards to the people around the facilities in question to determine risk level [40]. While this overall process and framework is useful to this research, the major difference between what the NRC must deal with and the UAS integration problem is one of scale and certainty.

The NRC primarily deals with fixed facilities. As a result, while the effects of an incident have some uncertainty due to environmental effects or the severity of the failure, the location and exposed population are fairly well known for each individual facility. This is certainly not the case for UAS that could eventually operate over the range of the entire NAS.

A brief summary of existing safety or certification methods applicable to UAS integration and their strengths and weaknesses appears in Table 1. The purpose of this table is to offer a qualitative comparison of existing methods and demonstrate through their shortcomings that another method is necessary for UAS integration.

Table 1: Summary of Methods and Explanation of Shortcomings

Method	Strengths	Weaknesses
COA Process	• Currently available and approved method	• Risk not quantitative • Lacks flexibility • Not adequate to meet needs of DoD and future Civil users
Certification Process for Manned Aircraft	• Comprehensive standards for aircraft and components • Quantitative requirements for failure rates	• Some standards may not apply to UAS • Manned aircraft standards may be impossible or expensive to achieve • No link between system failures and risk to bystanders • No provision to account for allowable operating environment
RCC Risk Criteria and NRC Methods	• Quantitative assessment of risk to public • Relies on probabilistic methods to assess risk	• More focused on fixed facilities and unique situations

Summary of Proposed or Current Certification Approaches

Finally, a review of the approach to UAS certification in use or proposed by organizations including those outside the United States is presented in Table 2. This list is shown to demonstrate several things related to the eventual discussion of certification in the Results and Discussion section. First, amongst the various entities in Table 2, there is little consensus on how to approach UAS certification. One theme is to use as many existing standards from manned aircraft that apply and publish additional standards for UAS, as necessary. Another theme from the European agencies is a desire or at least interest to use a Target Level of Safety (TLS) approach to certification, but no actual policy as of yet. The TLS approach will be discussed in much more detail throughout this paper. The last theme that emerges from the list below is that some agencies believe that there does not need to be any specific requirements for the smallest UAS, as evidenced by the CAP 722 approach. This policy will be explored in Part 2 of the thesis when the risk posed by a 4.4 lb air vehicle is examined.

.

Table 2: Certification Approach Summary

Organization	Document	Approach	Citation
NATO	STANAG 4671	Based on 14 CFR Part 23 and EASA CS-23. Augmented with UAS-Specific requirements as necessary.	[41]
Australia's CASA	AC 101	Experimental or Restricted Category Certification. A Safety Case approach is under development.	[42, 43]
ICAO	Circular 328	Document mentions using manned airworthiness standards augmented by UAS-specific standards but does not endorse a method.	[44]
EUROCAE Working Group 73	N/A	Discussion documents analyze using existing manned airworthiness approach or a TLS-type approach. Discussion recognizes importance of environment on UAS risk.	[45]
EASA	EASA E.Y013-01	Airworthiness codes, with differences considered under CS-21. Provision for Safety Target approach. Kinetic energy approach to classification.	[46]
Civil Aviation Authority Israel	UAV Systems Airworthiness Regulations	Range of Approaches from CS-23 compliance to demonstration of safety based on category.	[47]
Civil Aviation Authority (UK)	CAP 722	- Under 20 kg: No Certification Requirements - 20-150 kg: Light UAS policy - Above 150 kg: Follows EASA guidance	[48]
Federal Aviation Administration	Interim Operational Approval Guidance 08-01	COA for Public operators and Experimental for Civil. Provision for safety case for alternate compliance.	[33]

RELEVANCE

This topic is a timely one due to the important nature of UAS integration, the critical role that Safety plays in the airspace system, and the large amount of attention that this issue continues to receive in the industry and media. While typically referred to in the media as 'drones', UAS have gained widespread recognition because of their military impact in places like Iraq, Afghanistan, Pakistan and Yemen. The problem of safely integrating UAS into the NAS is also relevant because of the many potential benefits of integration and finally because integration is now mandated by law.

Value of UAS Integration

The integration of UAS into the NAS is extremely vital to the nation for several reasons. First, the military has become increasingly reliant on unmanned aircraft in their fleets. Second, domestic government agencies have many ways that they can take advantage of unmanned systems in areas such as law enforcement, border security, and disaster relief support. Third, the commercial use of unmanned systems is an untapped market that could create an entire industry if the entrepreneurial spirit of the nation's citizens is released.

The use of unmanned systems in the military has increased tremendously in more than a decade of overseas contingency operations. With the increased use of these systems in combat comes a corresponding need for domestic airspace for training and testing. Figure 6 below illustrates the exponential growth in UAS usage by the DoD and highlights the fact that this usage was nearly nonexistent just 15 short years ago. The Department of Defense already operates UAS from 63 different locations across the

Continental United States and that number is projected to increase nearly 70% by the year 2015 [14]. The chart in Figure 6 shows the annual UAS flight hours for DoD over the last 15 years. This figure does not include the hours accrued by the very small Group 1 UAS.

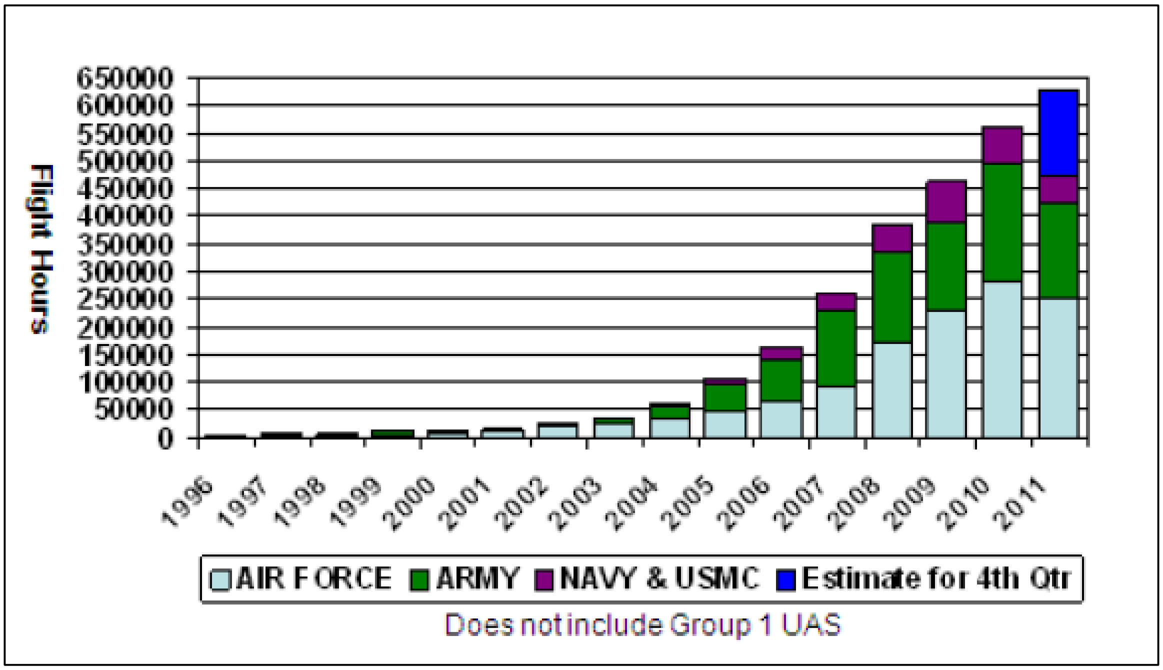


Figure 6: Department of Defense UAS Flight Hours [30]

Non-DoD public entities have already seen some UAS usage, primarily in the areas of law enforcement, border patrol and support for disaster relief operations. However, the demand for public UAS usage is much higher and there are many more opportunities for local, state and federal governments to benefit from unmanned systems. Urban law enforcement or surveillance missions represent possibly one of the most challenging integration problems due to the density of other aircraft and people on the ground. However, law enforcement employment of UAS enjoys the support of the majority of Americans, according to a recent poll by Monmouth University. In the national level poll about 80% of people surveyed favored the use of UAS for search and rescue missions, with 67% approving of UAS to track criminals and about 64% in favor of UAS usage for border patrol [49].

Beyond the use of UAS by public entities, there is a compelling argument to open the airspace to use by civil UAS. This market is virtually nonexistent now and thus has the greatest room for growth. While the possible uses are limitless, a list of potential applications published in 2004 includes such diverse areas as agricultural, advertising, mapping, commercial security, taking aerial motion and still pictures, communications and news gathering [50]. Although the economic impact of allowing civil applications for UAS is impossible to calculate precisely, the Association for Unmanned Vehicle Systems International (AUVSI) market forecast for non-government UAS shows a very healthy revenue growth rate for the next 10-15 years, as evidenced by Figure 7. They also show a corresponding growth in jobs related to the UAS industry during that time, many in high paying technical fields. A 2012 report by the Teal Group predicts that the UAS market will increase from $6.6 billion annually to $11.4 billion annually in ten years [51]. This forecast represents a market nearly doubling in that period.

In addition to the domestic UAS market, unmanned aircraft usage and employment has grown in other countries as well. According to two articles, one of which cites the General Accounting Office, over 70 countries have some form of UAS as of 2012 [52, 53]. This means that the U.S. risks falling behind other nations in the use and value of this technology if integration efforts remain too slow and restrictive.

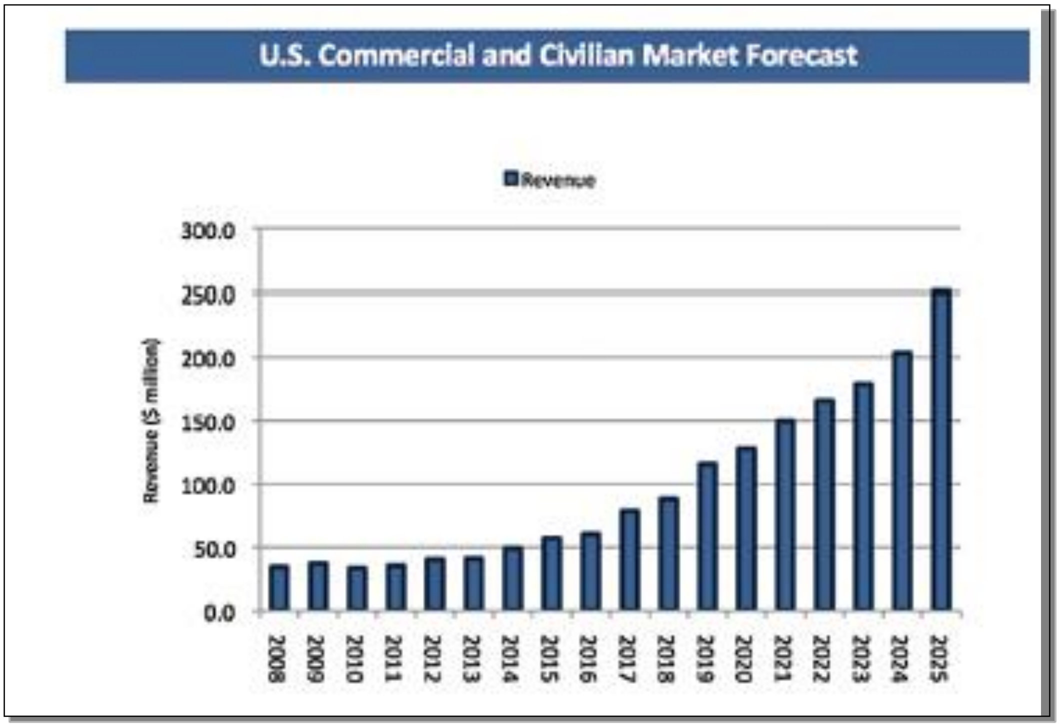


Figure 7: Projected Commercial and Civilian UAS Market [54]

Based on these compelling reasons for increased use of UAS in the NAS, few people are arguing that UAS should not be integrated. It is not a question of whether they will be included in the NAS or why, it is a question of when and how. These questions became more pressing with the very recent passing of a bill that puts UAS integration at a higher priority for the nation.

Legal Mandate

On February 14, 2012 President Obama signed a bill into law that had significant impact on UAS integration. Officially called the FAA Modernization and Reform Act, this legislation specifically targeted UAS integration. Key among the provisions were the following requirements:

- Within 270 days of enactment, the Secretary of Transportation must publish a plan to accelerate UAS integration that addresses, among other things safety, certification, and a sense and avoid capability
- Within 180 days the FAA must develop a plan to allow unmanned flight over certain Arctic regions
- By 2015 the FAA must develop 'operational and certification requirements' for public UAS integration

This law now forces the Federal Aviation Administration to develop plans and move toward eventual integration along specific timelines [12]. Prior to this law, many experts felt that integration would occur incrementally and deliberately; perhaps too slowly. It is now possible that integration could occur too quickly, because of the increased pressure from Congress, without the proper analysis to ensure integration is approached in a safe manner. Therefore, the topics in this effort are even more relevant than they were before the passing of this bill.

In addition to the requirements for integration planning, the law mentions two specific air vehicles with requirements for more rapid integration. The two vehicles in question are 4.4 pound law enforcement vehicles and 55 pound model aircraft. In order to explore the risk posed by these two classes of vehicles in more depth, the two weights in question will specifically be addressed in the second part of the research.

DEFINING THE PROBLEM

The previous section discussed why UAS integration is relevant to the nation. This section goes a step further and explains why integration is a problem that needs to be analyzed. There are several challenges that remain before UAS can be fully integrated into the NAS. While these challenges cover a large number of issues, they generally fall into two major categories. The categories are either related to regulatory or standards issues, or more operational and technological in nature. Again, this categorization is an oversimplification of the problem but most of the challenges either relate to supporting activities, or to the actual employment and integration of UAS.

Integration Challenges Overview

This thesis will show how the TLS framework can actually address both categories. In the first category, requirements for operator training and certification must be established. In addition, requirements for certification of the air vehicle or, more appropriately, the entire system must be created. Training and certification will be addressed again in the Future Work section, but certification is addressed here.

Some experts feel that the traditional certification approach will not be the most effective for UAS certification. There are several examples in the literature expressing doubts about using the current manned certification process and adapting it to UAS. A presentation to NASA experts on the UAS certification process raises concerns that there is inadequate safety and reliability data available to adopt such a process. In addition, the presentation cites the larger number of missions, uses and types of UAS compared to manned aircraft that may make a similar Type certification process untenable [55].

European agencies looking at the same problem also identify several obstacles to using their manned certification standards for UAS. Their notice of proposed rules on the issue discusses the fact that UAS operations require a control station that is not currently covered by any manned standards. They also raise the fact that 'Sense and Avoid' is not currently covered by any manned standards since that is a responsibility of the pilot and not inherent in the aircraft design [56].

The FAA's Sense and Avoid Workshop identified similar concerns about using the current Equivalent Level of Safety concept to establish certification standards for SAA. Ultimately, they concluded that it would be nearly impossible to determine whether a system was equivalent to a pilot in terms of SAA and stated that a different safety and certification process was necessary [57].

After identifying what several stakeholders in the certification process said about the issue, below is a summary of the major concerns that raise the potential for a different certification process for UAS compared to manned aircraft. First, UAS are not merely an aircraft but an entire system encompassing; at a minimum, the air vehicle, communication link and the ground control station. Safe operation depends on the safety of all components of the system so standards for the communication link and ground station would be required in addition to certification standards for the air vehicle itself. However, UAS and manned aircraft do not always operate in the same manner and their form and function are likely to differ even more in the future. For example, some UAS do not use a runway for takeoff and landing but instead use a catapult for launch and a net for recovery. Existing takeoff and landing standards would not make sense for such a vehicle. Future UAS may look and act more like birds or insects so design standards designed around propellers and traditional wings would not apply. UAS can also be much smaller and considerably lighter than their manned counterparts. Vehicles such as the Raven are already in widespread use by DoD and weigh several pounds and can be launched by hand. Prototype UAS already operate at weights of less than one pound and technology increasingly points toward UAS on the micro and nano scales. Therefore, the size and scope of some UAS will be vastly different than manned aircraft, which will always weigh at least more than the weight of a human and must have sufficient structure and weight to protect that human. In fact, it will be discussed later in this research that adding components to achieve standards designed for manned aircraft could actually add to the risk that UAS pose to bystanders.

All of these factors point toward the possibility that UAS may require a different approach to certification than the approaches currently used for manned aircraft. The approach that will be discussed in more detail later in this proposal is the Target Level of Safety (TLS) approach.

In the operational category of challenges, are those that will affect the entire NAS architecture and will determine how UAS will impact the other users of the NAS. One key challenge to integration frequently cited is the current inability of an unmanned system to 'See and Avoid' to comply with 14 CFRPart 91.113 which says that "vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft" [20]. Lost link procedures are another challenge that must be addressed. Both of these challenges can be addressed by the TLS framework and will be addressed in the Results and Discussion section.

The biggest challenge to UAS integration; however, remains the concept of safety. Demonstrating the idea that safety is a critical issue to this problem, a survey of stakeholder requirements was previously conducted by a team of graduate students at the Georgia Institute of Technology. A diagram of the major requirements and the sources they are attributed to appears below in Figure 8. The ovals on the left side represent characteristics of an integration plan desired or required by stakeholders in the problem. The individuals or organizations to the right represent the source of the requirement. These sources range from the Congressional testimony of key figures in government related to the UAS integration issue, pilot advocacy organizations, phone conversations with FAA officials, and the President of the United States' Aviation National Research and Development plan. Anything related to the safety requirement is highlighted in green [58-64]. Clearly a variety of stakeholders with different overall interests all feel that safety is an important consideration in any UAS integration process.

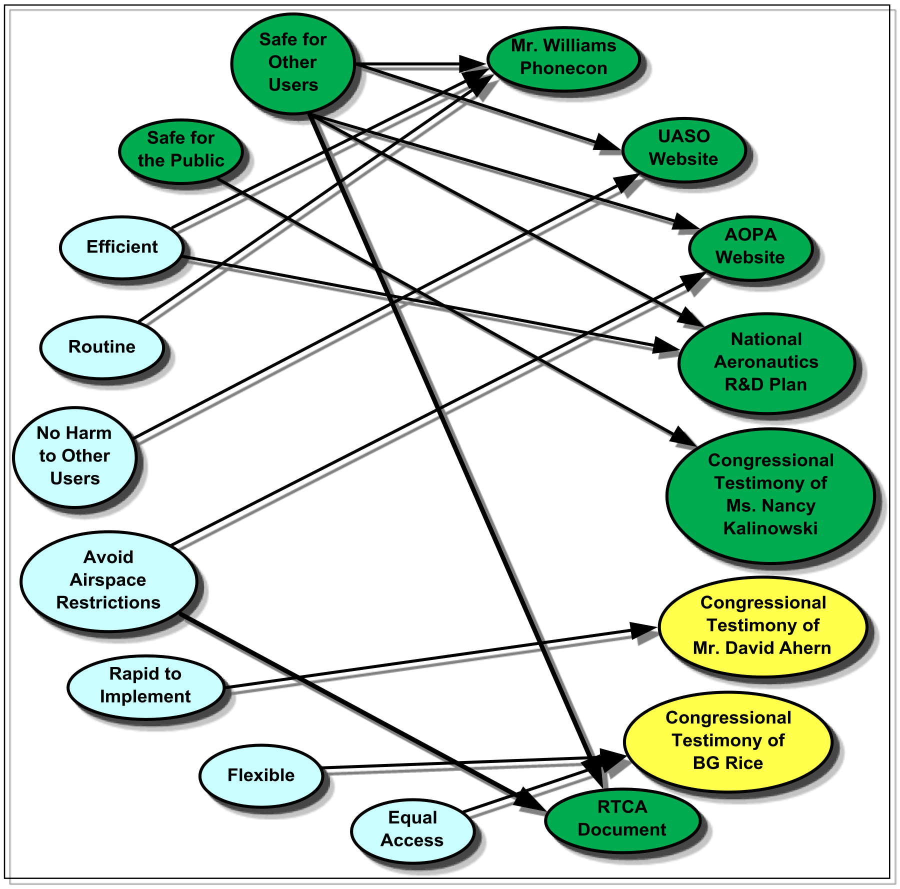


Figure 8: Stakeholder Requirements Summary

UAS are already operating alongside manned aircraft in contingency operations and from airfields and airspace that are extremely busy and complex. As a result, military operations already demonstrate that UAS can be integrated into a complex airspace system without catastrophic results. The real questions that remain for stakeholders are how safe do UAS need to be in order to be acceptable for integration in the NAS, would they meet that level of safety if integrated now, and what is the best way to achieve the desired level of safety if not already there.

The lack of agreement on safety metrics is certainly an inhibiting factor in the integration process. This fact was identified in the National Research and Development plan several years ago. A more recent example of this problem is present in the Association for Unmanned Vehicle System International (AUVSI) organization's attempt to create a common Code of Conduct for UAS operators. While certainly not meant to be a regulatory document, the first item in the code is the statement that UAS operators "… will not operate UAS in a manner that presents undue risk to persons or property on the surface or in the air" [65]. Unfortunately, no one in the community has identified what level of risk constitutes 'undue' risk. The topic of safety and how it has become the largest inhibiting factor delaying UAS integration will be discussed in more detail in the next section.

Identifying Knowledge Gaps

As described previously, safety remains a crucial concern for all of the stakeholders involved in the UAS integration process. However, as the stakeholder requirements review in Figure 8 reveals, there are other requirements as well. Among these requirements is the need to develop an integration plan that is flexible, one that allows for a high degree of integration, is adaptable to future changes, and allows for routine, equal and efficient access to the NAS for all users.

To this point in the paper, Safety has been clearly identified as a major component in any solution to UAS integration. Just focusing on the language in the 2012 FAA modernization bill that mandates UAS integration reveals numerous references to safety. For example, section 332 of the law, the first section that specifically addresses the UAS integration plan references safety eight different times [12]. The next section requires the Secretary of Transportation to assess which UAS "may operate safely in the national airspace system before completion of the plan" and "which types of unmanned aircraft systems, if any … do not create a hazard to users of the national airspace system or the public" [12]. If the Secretary determines such UAS exist, he or she must "establish requirements for the safe operation of such aircraft systems in the national airspace system" [12].

Another example of the importance of safety is in the ICAO Circular 328 on UAS. This document states that "The principal objective of the aviation regulatory framework is to achieve and maintain the highest possible uniform level of safety. In the case of UAS, this means ensuring the safety of any other airspace user as well as the safety of persons and property on the ground" [44]. Yet another example appears in the EASA document on certification which says that “With no persons onboard the aircraft, the airworthiness objective is primarily targeted at the protection of people and property on the ground” [46].

At this point in the process, language and meaning become critical. According to this law, a UAS that does not create hazards to users of the NAS is acceptable for use in the NAS. A complete absence of hazards, however, implies a perfect safety record. The law also goes on to say that if a UAS is safe enough, it can also operate in the NAS. Clearly, a distinct obstacle preventing UAS from operating in the NAS is a common agreement on Safety metrics. In other words, how safe is safe enough? Other countries are struggling with the same issues. The United Kingdom’s Civil Aviation Authority’s (CAA) lead on UAS, Gerry Corbett, stated that “What’s important [for UAV integration] is that they have to demonstrate an equivalent level of safety to manned aircraft, and that presents a series of challenges” [66]. The implicit challenges that Corbett refers to is how to determine if UAS able to meet required safety goals? It is with this focus that this research continues and identifies a gap in current approaches and methods to this problem.

In order to better understand the gap that needs to be filled, it is vital to first put the problem in context. Although there are many stakeholders involved in this process, the key stakeholders fall into two major categories. The FAA is the regulatory authority that must do two things in this process. One, they must create the regulatory framework for UAS integration to take place. A key component of those regulations will be the safety metrics that basically specify ‘how safe is safe enough’. Two, the FAA must determine or certify if a UAS meets the stated requirements before being allowed to operate in the NAS. The FAA serves as the gatekeeper into the NAS but they must first define the criteria for being allowed through the gate.

On the other hand are the UAS users, designers and manufacturers. These stakeholders need information on the regulations and metrics, namely the safety requirements so they can design and operate their systems properly. To continue the analogy, they need to know the requirements to get through the gate so they can ensure they meet those requirements before arriving to seek entry.

To examine this graphically, an example of the use of Fault Tree analysis appears below in Figure 9. In this case the System Failure rate represents a failure rate of the overall UAS and is the 'gate' that UAS designers and manufacturers must strive toward. If that value is fixed, a system designer can move to the left and allocate failure rates to sub-systems and components accordingly. In some cases, if already existing components are used, their failure rates are synthesized from left to right to determine an overall system failure rate.

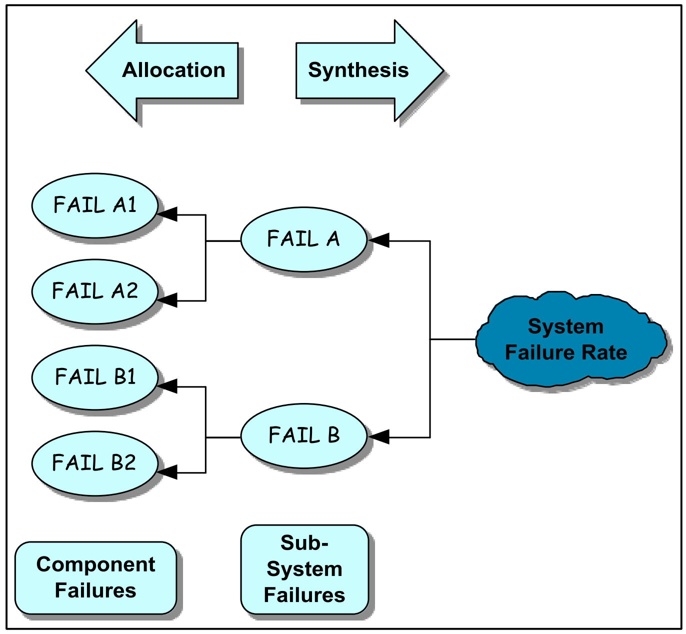


Figure 9: Role of Fault Tree Analysis

At this point, the question that remains is how to determine an appropriate system failure rate for any system in question. As discussed previously, a lack of reliability or a high failure rate does not necessarily translate into a high level of risk or low level of safety. During the certification process, it is a combination of the severity of a hazard and the consequences of the hazard that determine the allowable probability of the hazard occurring [67]. The concern of the FAA, or other regulatory agencies for that matter, is safety and not reliability. Therefore, it is necessary to look beyond the system failures and determine what impact or effects those failures have.

To determine the effects of failures, a tool such as the Failure Modes and Effects Analysis (FMEA) or Failure Modes and Effects Criticality Analysis (FMECA) can be used. This procedure requires the analyst to examine each failure mode and examine not only the effects of that failure but its severity [68]. Based on the earlier definitions, the failure rate or probability of failure, combined with identification of the effects or hazards, and the severity of those hazards constitutes the definition of risk. Determining the effects of failure modes is very important because the severity of the effects will determine whether mitigation techniques are required [69].

A representation of the combination of Fault Tree Analysis (FTA) and FMEA tools into one diagram appears below in Figure 10. This diagram; often referred to as a bow-tie diagram due to its shape, can be used in a couple different ways. An example taken from an FAA report on incorporating the Traffic Alert Collision Avoidance System (TCAS) on UAS also appears in Figure 11 to provide an example of this diagram actually used in this problem. Ale, et.al. point out the value in using bow-tie diagrams in both accident analysis and prediction, as well as an interface between cause and consequence in decision-making [70].

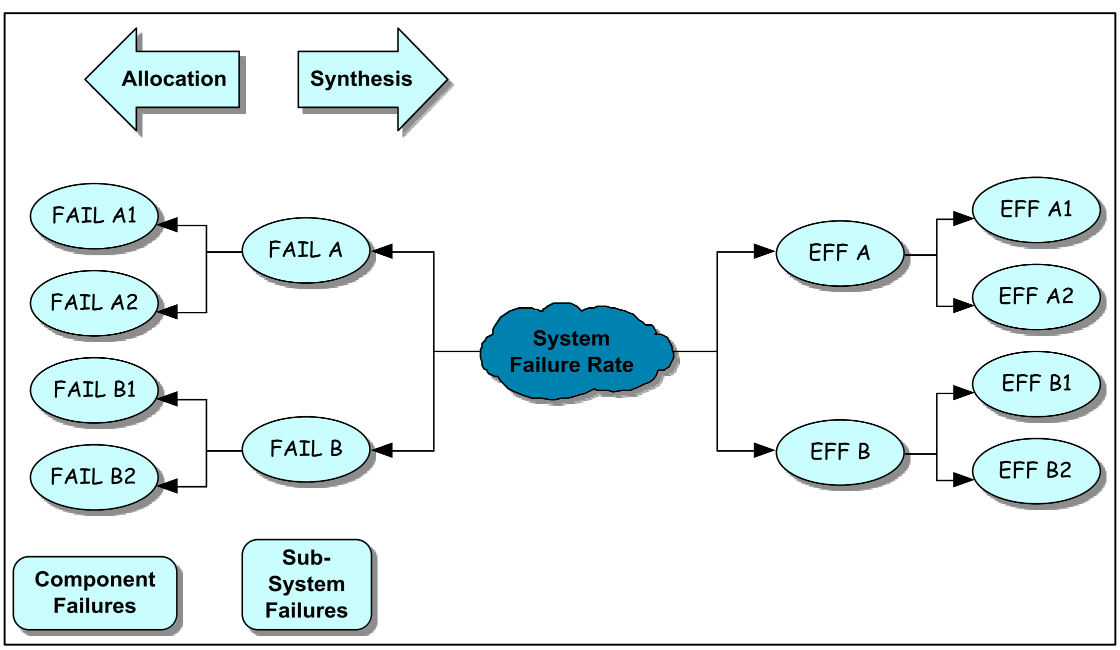


Figure 10: Example Bow-Tie Diagram

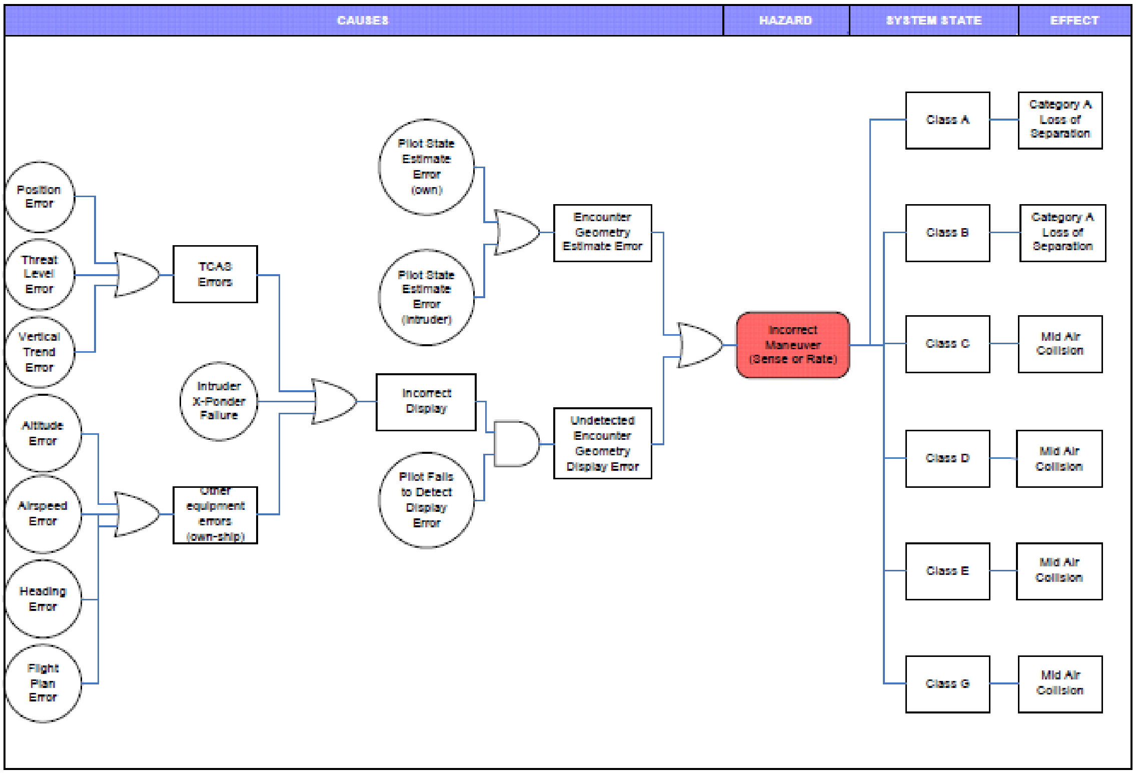


Figure 11: Bow-Tie Diagram for TCAS on UAS [71]

If one wishes to design a new system, the analysis could begin on the right of the bow-tie diagram. When dealing with a public issue like aviation, energy, space travel or highway transportation there will likely be some maximum allowable risk level. The designer of a system that must operate under those requirements would analyze all of the potential hazards or effects of the system and work right to left to determine the maximum allowable system failure rate to meet the safety requirements. Then the designer could allocate that threshold failure rate to the sub-systems and components to ensure that the system meets the overall failure rate. This process of identifying failures and their effects to determine reliability requirements is outlined in ARP 4754 under the Functional Hazard Assessment (FHA) description [35].

In another situation, a designer that must work with already existing components or sub-systems could work from the left side of the diagram to determine the overall system failure rate. Then the FMEA could be conducted to determine the impact that system would have on its environment or the people around it by continuing to the right.

In the UAS situation the two main entities in the integration problem, the FAA and the user community must essentially work from both ends and meet in the middle. The FAA must start on the right side, analyze the impact of UAS failures and set the system-level failure rate requirements. Then the UAS designers would design their systems to include vehicles, ground stations, and communication links to meet those requirements.

In manned aviation, the effects that are analyzed on the right of the diagram are confined, in large part, to the system itself. However, all of the UAS applications in the near and mid-term involved air vehicles with no occupants. Therefore, safety in this context must be related to people outside the air vehicle. The difference between these two approaches can be seen in the summary in Table 3. The FAA targets for air vehicles are reliability targets since they limit the number of failures that a vehicle can have, with no mention of the consequences other than that the failures are catastrophic or would result in the loss of the vehicle and or the passengers. In other words, the first four values in Table 3 are primarily limited to the vehicle itself. In contrast, similar metrics in the lower portion of Table 3 reveals a more direct concern with the effects that the vehicles create, or the fatalities that occur, as opposed to focusing mainly on the system itself.

While UAS applications may eventually involve passenger travel, the more pressing concern is whether UAS operations will put people in other aircraft or on the ground at risk. Therefore, the focus of the literature search was on the risk associated with unmanned vehicles causing deaths to people either through a midair collision with manned aircraft or due to a ground impact. This is an important distinction.

Table 3: Comparison of Risk/Safety Targets

Organization:	Application	Value:	Metric:	Source:
FAA	Single, Reciprocating Engine, Less Than 6000 lbs, Non-Transport Aircraft	$< 10^{-6}$	Catastrophic Failures per FH	[72]
FAA	Multi-Reciprocating Engine or Turbine Engine over 6000 lbs, Non-Transport Aircraft	$<10^{-7}$	Catastrophic Failures per FH	[72]
FAA	Aircraft Over 6000 lbs, Non-Transport Category	$<10^{-8}$	Catastrophic Failures per FH	[72]
FAA / EASA / SAE	Commuter / Transport Category Aircraft	$< 10^{-9}$	Catastrophic Failures per FH	[35, 73, 74]
Range Commander's Council	Space Flight and Launch Tests	3×10^{-5}	Fatalities per Mission	[75]
FAA	Launch Vehicle Safety	30×10^{-6}	Fatalities per Mission	[76]
NRC	Cancer Fatalities due to Nuclear Power Plants	2 x 10-6	Fatalities per Year	[77, 78]

Assuming that near-term UAS usage will be completely unoccupied is a key distinction because it changes the nature of the safety concerns for UAS from one of concern about the safety of the vehicle itself to concern about the people whom the UAS can potentially harm. Although seemingly subtle, this difference is crucial because now the environment that the UAS operates in is as or more critical to the safety analysis as the understanding of the safety characteristics of the system itself is. This difference also reinforces the inherent difference between the terms reliable and safe. The certification process for manned aircraft stresses reliability by mandating specific reliability rates with the understanding that failures of the system can cause unsafe conditions for the occupants. However, for an unmanned vehicle, an unreliable vehicle operated in sparsely populated areas could be safer than a more reliable vehicle operated in a densely populated area.

The focus on risk outside the system in question or external risk is not new in the aviation community. A group focusing on risk around airports in the Netherlands from the National Aerospace Laboratory (NLR), which will be referenced again throughout the paper, discussed this concept for manned aircraft. They cite that the focus on external risk started with the nuclear and chemical industry because of the hazards associated with these operations and their proximity to the public. Unlike these industries, however, it is more difficult to contain the risks associated with aviation because aircraft operations are not static by nature [79].

The NLR study attempted to assess and quantify the risks posed by aircraft operations around Schiphol airport, due to a crash that took place in a populated area and the desire to expand operations at the airport. The study tried to develop tools and methods to predict the likely location and consequences of a crash, based on specific and known flight patterns in the area. However, the UAS integration problem is much broader and less defined.

Because of these distinctions, a gap in the knowledge was identified that must be filled for this process to progress. That gap, placed in context in Figure 12, has been an understanding of the effects that a UAS would have beyond the system itself or on its environment. Environment in this context refers to the people on the ground and other users of the airspace. These effects, referred to as terminal effects, after the convention used in ballistics to refer to the "interaction between a projectile and a target" [80].

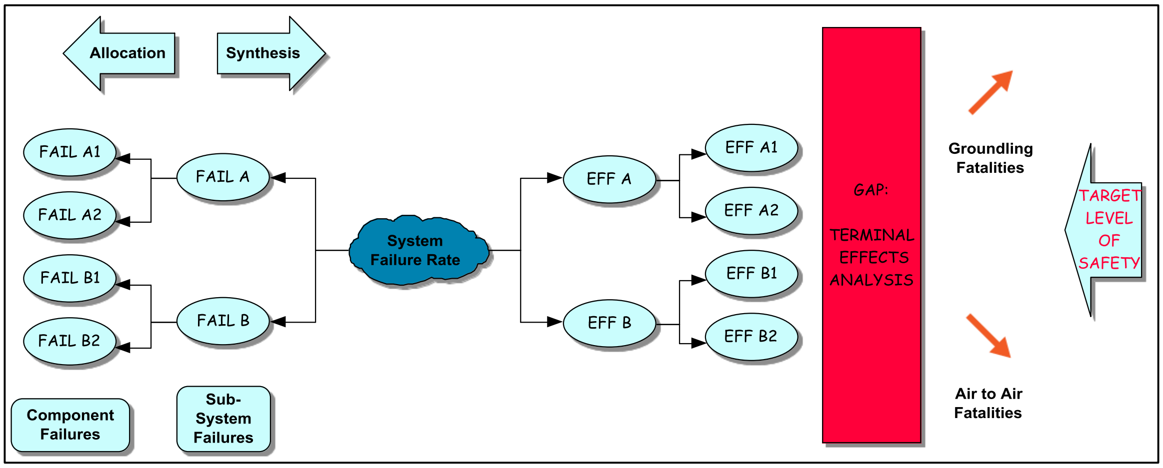


Figure 12: Depiction of Gap in Process

In order to set a risk threshold, or a safety target on the right hand side of the document, one needs to understand the effects that UAS will have beyond the system itself to work back to the left and set system failure requirements. These effects can come in many forms. For example, stakeholders can try to limit injuries, property damage, or fatalities. Injuries and fatalities can consist of third-party fatalities on the ground and fatalities caused by air to air collisions with other airspace users. Whichever metric is chosen, the effects must be understood to properly close this gap and set the requirements necessary in the middle of the diagram. Based on this understanding of the fundamental problem associated with UAS integration and the gaps in knowledge related to the effects UAS operations would have on people outside the system, the author conducted a literature review to identify potential ways to address those gaps.

LITERATURE REVIEW

There is already a substantial amount of research and information available on the topic of UAS integration, most of it very recent due to the nature of this topic. Perhaps the most documented aspect of this problem is the one that addresses avoiding air to air collisions and is referred to under various names such as Sense and Avoid, Separation Assurance and Collision Avoidance. There are also several studies aimed at estimating the risk to people on the ground from a UAS crash. There are fewer studies that address the problem in a comprehensive framework encompassing multiple aspects of safety and integration. Finally, the author did not discover any efforts in this area that attempted to build a framework to aid decision makers in choosing the proper combination of integration and risk mitigation measures based on some established criteria. The following sections will summarize the studies discovered to date.

Target Level of Safety

The section on Defining the Problem identified the need for a framework that could close the knowledge gap between UAS reliability and safety. One method that appeared throughout the literature on this topic was the Target Level of Safety approach. There are multiple arguments for the Target Level of Safety concept in the literature surrounding UAS integration. In fact, the national level Research and Development plan signed by the President of the United States indirectly mentions the approach in their near term goals for UAS integration. In that document, the goal for UAS is to "Define the appropriate target level of safety and the process for evaluation" [60].

Haddon and Whittaker define the ‘Safety Target’ approach as a “top-down approach which focuses on safety critical issues which could affect achievement of the safety target” [81]. The advantages they cite to such an approach are the fact that the user can focus on important risks and do not have to comply with “a comprehensive code of requirements covering all aspects of the design” [81].

One of the more favorable endorsements of TLS is the report of the FAA sponsored Sense and Avoid workshop discussed previously. This workshop, which was only focused on the SAA issue and not all aspects of integration and safety, did recommend that the Target Level of Safety approach was the best option for establishing standards to comply with or meet the intent of 14 CFR Part 91.113 or ‘see and avoid’ [57]. Overall, the workshop focused on several reasons why TLS was the best choice. First, it is quantifiable so it would be less open to interpretation. Second, the TLS approach would help in the process of allocating failures to both equipment and procedures. Finally, the TLS approach provides for a comprehensive analysis of the system and the environment [57].

The Europeans, who are arguably ahead of the United States on the topic of UAS integration, also proposed using a TLS approach to analyzing this problem. A key component in the European’s approach is that the safety target allows for a combination of design and operational requirements to achieve a target and that this approach eliminates the requirements to comply with a lengthy set of standards [56].

Interestingly, the FAA already employs a type of TLS process in the area of launch vehicles. The regulations on Reusable Launch Vehicles (RLVs) requires that an applicant demonstrate that the launch of any vehicle not pose a risk greater than a specific value [76, 82]. This approach makes sense for RLVs because, in many cases, these designs may be unique or at least of such a low rate of production that certifying them using an approach similar to manned aircraft would be infeasible.

The TLS approach differs from the current FAA system of equivalent level of safety. In the latter approach, anyone proposing a new component design or design change must be able to show that the proposed equipment can meet the equivalent level of safety (ELOS) of the component it is designed to replace [83]. This approach assumes that the overall system or aircraft is similar to other certified aircraft and that replacing a component with one that is as safe or safer than the old component will ensure overall system safety as well. As previously discussed, this approach is not a good choice for UAS since they do not always match existing aircraft in the way they are designed, built and operated.

A joint FAA / Eurocontrol report on separation modeling also speaks favorably of a TLS approach. The report mentions the fact that the approach is grounded in reality and can leverage historical data as a starting point. The report also points out that the TLS approach focuses on the end result, which is typically the most important to the community in question. The fact that a TLS approach focuses on results is in direct contrast to an example provided by the President of the AUVSI during a 2012 to Congress. In the hearing, the organization's President touted UAS safety by citing the city of Arlington, Texas and the fact that their law enforcement UAS program had developed "pre-flight checklists, flight and squawk logs, training protocols and a standard operating procedure" [84]. All of these examples are procedural in nature and say nothing about whether the UAS in question have actually caused any harm or achieved any specified level of safety.

Finally, one of the drawbacks of the TLS approach is highlighted in the FAA / Eurocontrol report and is that there must be some way to prove that a new system will meet the TLS before being implemented, which can be difficult [85]. The major thrust of this current effort is to show that the data is available to populate a prediction tool that can support the TLS approach.

Another argument that surfaces in a newer, systems-based approach to safety is the need to address more complex safety issues that often involve the interaction of the intended design with the environment. Leveson, in her work on the STAMP safety methodology, addresses the need to approach safety from a total systems perspective which includes not just the hardware that the engineer designs, but the human and environmental interaction [86]. The inclusion of the environment into the TLS approach to UAS integration is one that will resurface when discussing the modeling and simulation effort of this thesis.

The concept of a TLS in the form of a Fatal Accident Frequency Rate (FAFR) is introduced in a paper on building chemical plants. The FAFR is a number of allowable fatalities per some time metric. In a similar manner, the author discusses the need to understand the risk imposed by building the plant as well as determine what level of risk is acceptable. He states that although the FAFR method is not perfect, it is the best option to quantify and accept risk [87].

Another proponent of a TLS-type approach to UAS integration is Clothier, et. al. [88]. In an article on the topic of UAS certification, they discuss the difficulty in certifying UAS in the same manner as manned aircraft and cite two main reasons. One, UAS are simply built differently and are changing so quickly that specified standards may not be applicable. The other aspect they address is that the aim of manned aircraft certification is mainly to protect the occupants, while the aim of UAS certification should be to protect the public. The article lists six criteria that should be applied to any UAS certification standards which are:

1. Justifiable or be based in risk and safety
2. Flexible enough to account for the variety of UAS
3. Systematic
4. Objective
5. Practicable
6. Cognizant of the costs associated with undue regulations

The author will show later in this paper that the TLS framework proposed in this thesis meets those six goals.

Finally, several other studies have proposed a TLS-type approach to the UAS integration problem, or with respect to manned aircraft flights around airports. These studies, which will also be discussed in the Integration Framework section include Evans [89], Waggoner [90], Weibel [91], Clothier [92] and Burke [93], to name a few.

Ground Risk Studies

Also relevant to this research are past efforts on quantifying the risk to people on the ground due to UAS accidents. This area is particularly important to UAS operators who wish to employ unmanned systems over urban areas for missions such as law enforcement or surveillance. Ground risk studies are also referred to as third-party wirk studies because the public on the ground is not associated with the UAS involved nor are they willing participants in the NAS. There are several contributions to the literature on third-party risk that are important to cover.

An Australian study first highlights the major differences between studying UAS safety and manned aviation safety. This is a key concept that fits in with the premise in this effort that requires a paradigm shift in the safety process for UAS. This study points out that safety for UAS is not about the safety of the vehicle but more about the safety of those people around the vehicle. The paper goes on to develop an analytical framework to understand UAS risk to people on the ground using a risk contour approach where risk is a function of population density and system reliability. However, the contour approach was applicable to a particular area the paper analyzed and not an area comparable to the entire NAS. The paper also analyzes four different target levels of safety, although the author refers to them as equivalent levels of safety, based on either historical data or societal acceptance of risk [94].

Dalamagkidis, published an important paper on ground risk that focuses on the energy at impact of various UAS vehicles. He also linked the ground risk to population density but looks closely at the amount of kinetic energy of a falling air vehicle and correlates that to the threat of fatalities on the ground [95]. It is also important to understand the impact that kinetic energy will have on shelters and how that will affect safety on the ground, particularly in urban environments. One of the objectives of the current research is to further explore the relationship between air vehicle energy and the potential for shelter penetration on the ground.

A study from the Netherlands analyzed safety around airports in that country based on manned flights. An important aspect of the Netherlands study is that they linked the size of a debris field to the weight and size of the air vehicle [96]. This information can better help understand a more realistic threat area on the ground due to falling air vehicles since the vehicle may not necessarily remain intact all the way to impact or after impact in the event of a crash. This method for the estimation of an impact area will be examined in more detail and compared to other methods in the section on the Ground Risk model.

A study conducted in 2001; timely due to its proximity to September 11, 2001, provides excellent statistical data on the risk to people on the ground due to aircraft crashes. This study outlines the historical data of ground risk based on the type of aircraft involved (commuter, general aviation, etc.) and also correlates ground risk to proximity to an airport. This information will be important since statistics show that most aircraft crashes occur around takeoff and landing, thus creating a greater level of risk around airports. This study also uses the concept of a ‘groundling’ or a third-party person on the ground unrelated to the operation of the air vehicle. It is this category of people that stakeholders should be concerned with since they are bystanders and should have the least exposure to risk [97].

There have been several efforts already that attempted to estimate the risk posed to third-party people on the ground due to UAS operations. Most of these have been very general and used simplifying assumptions for many of the key parameters required.

There have also been several studies on the risk to third-parties due to manned aircraft flight around airports. However, these have been narrowly focused around particular airports and lack the generality required for a study of this type [98]. It is important to discuss an overall casualty estimation concept and each of the elements of that concept will be discussed.

A casualty estimation technique, based on an equation similar to Equation 1, appeared in Burke's work [93] and the Range Commander's Council handbook on UAS risk [39]. In this equation, the value for E_c is a measure of the risk posed to third-party persons, or estimated casualty rate. The variable λ_{System} is a measure of UAS reliability and is the failure rate of the system for those failures that would cause an inability to maintain coordinated flight. All of the other terms account for the terminal effects an unmanned air vehicle would have on the public in the area of operations.

$$E_c = \lambda_{System} * \rho_{Population} * P(Fatality|Impact) * A_{Impact} * SF$$

Equation 1

In other words:

1. How many people are in that area that could be affected ($\rho_{Population}$)?
2. What protection does shelter offer the people inside (SF)?
3. How large is the area affected by the air vehicle impact (A_{impact})?
4. Of the people affected, how many people are fatalities (P(Fatality|Impact))?

This study also incorporates a Target Level of Safety concept into the analysis of UAS safety and sets that threshold at 1 death per 10,000,000 hours. This threshold is very stringent and the analysis in this thesis will discuss whether a safety target of that magnitude is appropriate. The Burke study uses a geometry-based, non-linear estimation for impact area. Burke uses a variation of a swept area calculation for the lethal area based on the wingspan of the vehicle. This calculation uses geometry to estimate the amount of area on the ground that the UAS would 'sweep out' during an uncontrolled descent.

In Table 4 is a summary of all of the major studies relevant to the topic and how they each account for the major parameters associated with ground risk. It is the intent of this thesis to explore the unknowns listed above and populate them with as much information from reliable sources and previous studies as possible, instead of relying on assumptions, for several reasons. A Dutch report on airport safety, when describing the uses of third party risk models, highlights the need for models to be both accepted by the community, and be capable of providing decision makers with valid analysis tools [79]. This effort intends to show that adding the layers of realistic input to the model will both make the model better capable of predicting casualties and better capable of providing feedback from analysis.

Table 4: Ground Risk Parameter Comparison

Model Parameter	Clothier	Evans *	Waggoner	Burke	Dalamagkidis	Weibel
Population	Uniform	Uniform	Uniform	Uniform, Time-Weighted Average	Uniform	Uniform
Shelter Effects	N/A	N/A	N/A	Linked to Population Density Variable	Incorporated into Casualty Calculation	Estimated Based on Vehicle Class
Impact Area	Geometry-Based (Steep and Gliding)	Weight-Based (Non-linear)	Geometry-Based (Gliding)	Geometry-Based (Swept Area)	Geometry-Based	Geometry-Based (Planform Area)
Casualties	All	30% in Impact Area	Left to User to Determine	All above 49 ft-lbs of KE	Based on Log Curve from RCC	All, if Penetration Occurred
Validated	No	No	No	No	No	No

* Not originally intended for UAS

Midair Collision Studies

The integration challenge that has received the most attention, based on the result of the literature review, is that of overcoming the requirement in 14 CFRPart 91.113 to "see and avoid" other aircraft "when weather conditions permit" [82] . There is substantial information in the public domain regarding midair collisions and collision avoidance since this is a problem that existed before the question of integrating unmanned systems. Understanding the risk of air to air collisions was also an important facet of the implementation of systems such as TCAS and the Automatic Dependent Surveillance – Broadcast or ADS-B. The interest in UAS integration has only added to the literature on this topic.

Some of the most comprehensive academic work in this area comes from the Massachusetts Institute of Technology's Lincoln Lab and the work of Dr. Roland Weibel, Dr. R. John Hansman and Dr. James Kuchar. Dr. Weibel's work for the MIT International Center for Air Transportation (ICAT) used a gas particle model to represent the possibility of aircraft collisions. The study used information from the FAA on traffic density at different altitudes and explored the risk of collision near and away from established airways [91]. While the correlation of risk to airways was important at the time, it will likely be of less importance in the future as the FAA transitions to more satellite-based navigation under the Trajectory-Based Operations (TBO) concept [99, 100].

Additional work on encounter models analyzed the risk of Near Mid-Air Collisions (NMAC) for aircraft using TCAS in environments with both other cooperative and non-cooperative traffic [101]. This work is valuable because it provides statistics on how using a system such as TCAS, which could represent an already established avoidance system, affects the risk of NMAC. This work actually built on an earlier report from the same group that looked at collision risk for aircraft equipped with transponders only [102]. In both cases, the reports in question analyzed cases where it was likely that there would be some air traffic intervention prior so the encounter and cases where that would not occur such as in uncontrolled airspace. All of these studies are valuable since they provide statistical results of their dynamic modeling efforts that can be leveraged into analytical models.

A study on existing NMAC provides a statistical basis to compare the results of the models and also establishes a safety benchmark to compare any future changes to.

That paper, published from the University of Illinois discusses causes for and conditions when NMACs occurred with manned, civil aircraft [103].

A British study on separation assurance provides different examples of how models can be used to predict NMAC rates under a general TLS framework [104]. The benefits that this paper offers is that it provides examples of simplified models, and also contains statistical data on the effectiveness of the current ability of pilots to ‘see and avoid’ other aircraft. This information was important to allow comparison of different methods of meeting the requirements of 14 CFR Part 91.113.

Finally, another study from the Carnegie Mellon Institute provides additional comprehensive analysis of previous mid-air collisions and where they occurred. This paper also discussed in detail the stated and derived requirements that stem from 14 CFR Part 91.113 and compares several proposed technological means of achieving this requirement. Again, this data is useful in both establishing a safety baseline for air to air collisions and providing a starting point for later comparisons of different risk mitigation measures.

For example, there has been a significant amount of discussion on the requirement for a means for UAS to replace the pilot’s perceived ability to ‘see and avoid’ other traffic with the ability to ‘sense and avoid’ other air traffic. However, there is nothing in the literature to suggest a required level of effectiveness for such a system. The level of effectiveness is a metric that combines reliability with the ability to actually achieve an intended purpose.

No system is either completely reliable or completely effective. In order to properly develop a SAA system, designers need to know how effective the system must be at avoiding other airspace users and under what conditions. The framework outlined in this thesis can help set those standards by linking the failure rate of a SAA system, to the percentage of NMACs the system prevents from being MACs all to the maximum allowable casualty rate set by stakeholders. The concept of linking effectiveness rates for mitigation systems will be discussed in more detail later in this paper.

A summary of the major studies and their approach to the various aspects of a required midair collision model appears below. Later, in the section on the model used in this research, an additional comparison will be offered to demonstrate the techniques used in this thesis.

Table 5: Midair Risk Parameter Comparison

<table>
<tr><th>Model Parameter</th><th>Clothier</th><th>Evans *</th><th>Waggoner</th><th>Burke</th><th>Dalamagkidis</th><th>Weibel</th></tr>
<tr><td>Model</td><td rowspan="5">N/A</td><td rowspan="5">N/A</td><td>Gas Model</td><td rowspan="5">N/A</td><td>Gas Model</td><td>Gas Model</td></tr>
<tr><td>Avoidance</td><td>Derived from Historical Data</td><td>Derived from Requirements</td><td>N/A</td></tr>
<tr><td>Effects on Aircraft</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Casualties</td><td>Based on Passenger Estimates</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Validated</td><td>No</td><td>No</td><td>No</td></tr>
</table>

Debris and Hazard Studies

UAS are not the first airborne technology to pose a risk to people on the ground. Manned aircraft, artillery, rockets, missiles and spacecraft have all operated over or near populated areas. Therefore, these topics provide another interesting source of information on the risk of death or injury to people on the ground as a result of falling debris. The two focus areas in particular that provide insight into this risk are studies dealing with safety around impact ranges and studies conducted after the tragic 2003 breakup of the Space Shuttle Columbia. The primary fact that all of these studies reinforce is that an air vehicle of all but the most trivial size (less than approximately 4 pounds) would have enough kinetic energy to cause fatalities to exposed individuals.

A source that can serve as a very good example of the type of approach required for this research comes from a reliability guide used by the FAA that pertains to Reusable Launch Vehicles (RLV). This guide, which focuses on an expected casualty metric determination for proposed launch missions, outlines two suitable techniques for estimating casualties. The first technique is known as Reliability Allocation and is depicted in Figure 13 below. Without going into exhaustive detail on this technique, the method starts out with some system-level reliability goal. Then the methodology uses input from models and historical data to allocate that reliability requirement or goal based on mission phase and subsystem. The methodology then uses reliability analysis tools to verify that the system can meet the reliability requirements and goals.

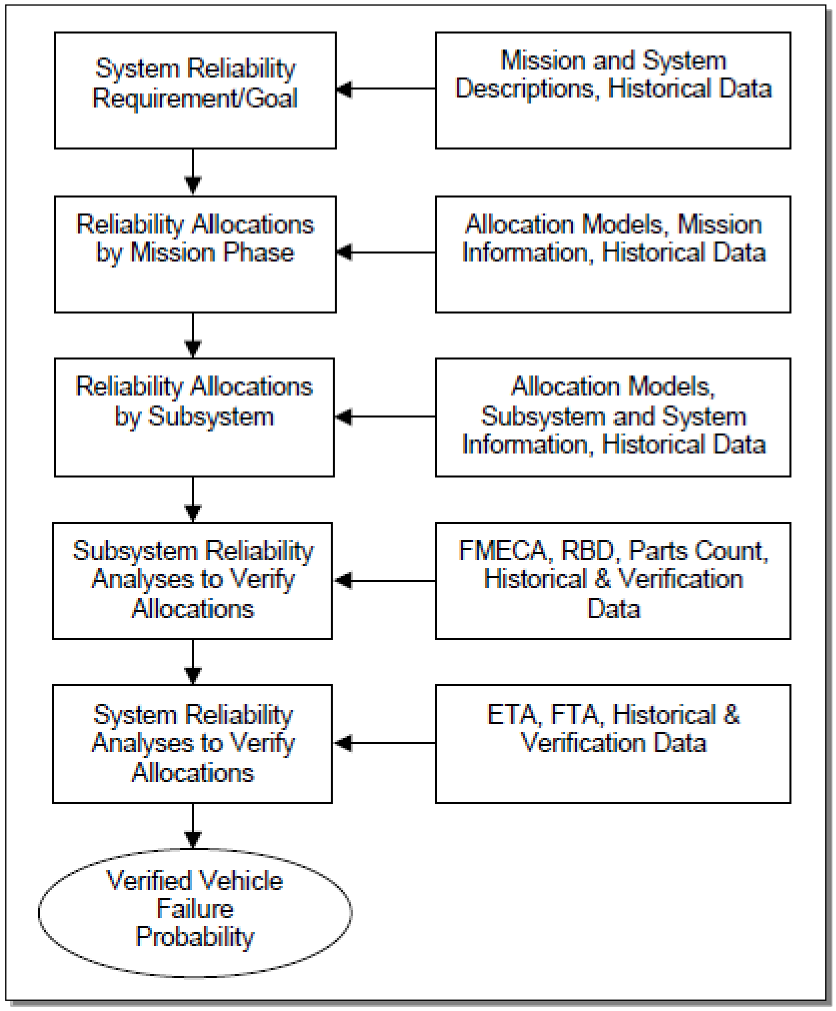


Figure 13: FAA Reliability Allocation Technique [105]

This methodology is an extremely important example that can help shape the framework used in this thesis. Because the goal of the FAA's RLV reliability guide is to estimate casualties on the ground potentially caused by launches, the application is very similar to the requirement to assess and mitigate risk to the public from UAS. In addition, this technique analyzes mission segments in the process of estimating risk which is similar to the need to take the mission or environment into account when assessing UAS risk.

The basic equation used by the FAA to estimate casualties during space launch event appears below as Equation 2. The components of this equation are as follows:

- E_c is the Expected Number of Casualties for a particular launch
- n is the number of events that could potentially cause a casualty
- P_i is the probability that each event occurs
- A_{ci} is the area affected by that particular event
- D_{pi} is the population density in the area affected by that event

$$E_c = \sum_{i=1}^{n} P_i * A_{ci} * D_{pi}$$

Equation 2 [106]

This technique is also used by several of the other studies pertaining to UAS safety to account for the risk to third-party persons. The advantage of this equation is that each potential fault can be analyzed independently to determine the probability of occurring. In addition, the area affected, and the population density of the affected area is relatively easy to determine. However, this equation was also created to determine the risk due to spacecraft debris or smaller pieces of the launch vehicle spread out over a large area. The question remains whether this technique is applicable to a larger object such as an entire unmanned aircraft crash landing into a non-uniform geographical area such as an urban setting. This question will be explored in greater detail during the section on the modeling and simulation efforts of this paper.

Despite the basic nature of this equation, this research will eventually incorporate the concept of this model for casualties into a more advanced model for estimating casualties on the ground due to a UAS incident. What will be replaced is the more basic estimation of the area affected and population density with a more realistic estimation of the terminal effects of a UAS incident.

The other technique for casualty estimation espoused by the FAA is the Probabilistic Risk Assessment (PRA). Absent in this technique is the initial establishment of safety or reliability goals. The PRA simple analyzes what events can cause failures and under what scenarios. Then the methodology utilizes reliability tools to develop failure models and leverages Monte Carlo simulations to estimate the probability of those failures occurring. Again, this methodology offers several useful tools that can be combined into the framework that will be discussed in the next section.

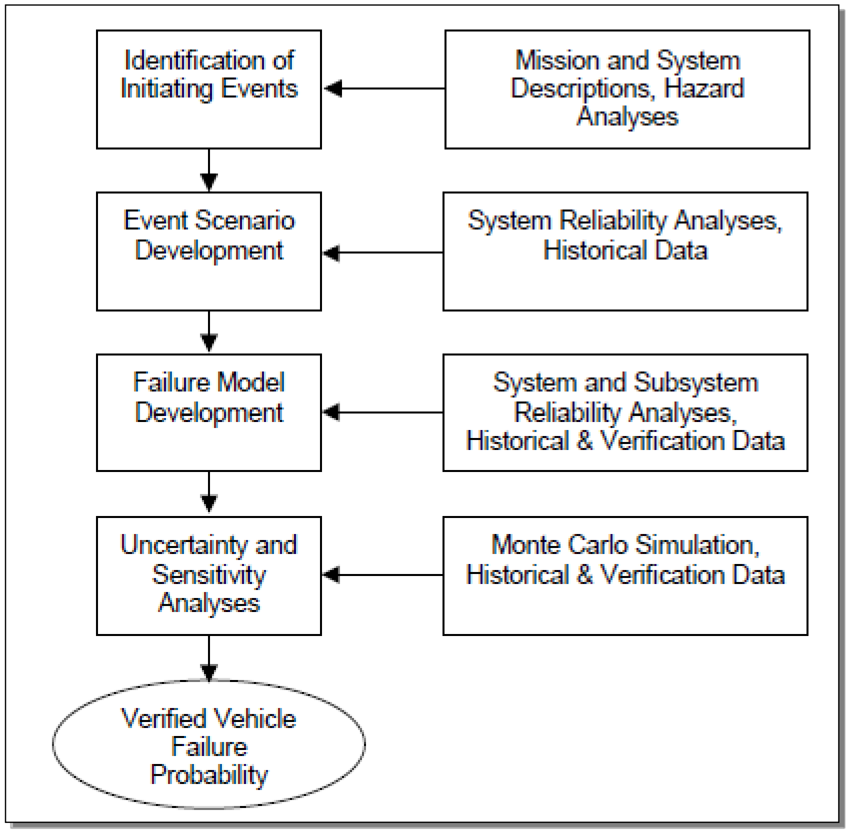


Figure 14: FAA and NASA Probabilistic Risk Assessment Methodology [105]

A Sandia National Laboratories report on ground risk due to debris outlines the risk of fatalities based on kinetic energy. This report, which draws on experimental data conducted on cadavers, animals, and simulated human bodies also goes into great detail about the risk of injury or fatality based on where on a human being the impact takes place [107]. While this level of detail is too great for the purpose of this research, the report does provide statistics that relate the probability of a fatality to the kinetic energy of a collision. This information can definitely assist when analyzing the threat posed by smaller UAS.

Studies on the risk of debris damage caused by the breakup of the Space Shuttle during reentry provide data on what is considered acceptable risk from a societal point of view. They also start to link the risk of injury to the type of shelter available to people on the ground. The Columbia Accident Investigation Board (CAIB) report has data that links the energy on impact to the probability of penetrating building made of various materials [108]. This information can be used to examine the risk of fatalities on the ground to non-exposed personnel.

There are several studies and reports that reinforce a value for the kinetic energy required to kill an exposed human. While too numerous to discuss individually, all of these reports agree that approximately 50 ft-lb of energy is all that is required to cause a fatality for an exposed individual [75, 76, 107, 109, 110]. This fact will be a contributing piece of information into the analysis of ground risk.

There are also studies on the damage that debris can cause to different structures based on either kinetic energy or pressure, which must be based on decelerations estimates to generate the impact forces required to calculate pressure. All of these studies are helpful in estimating a more realistic risk to third-party persons, some of whom will be inside structures during a UAS crash [108, 111, 112].

Integration Frameworks

The last major category in the literature search involves frameworks that are more comprehensive in nature in the way they address UAS safety. There are few overall Target Level of Safety frameworks related to UAS that originate in the United States and none also incorporate an aspect of decision-making into the work. The Europeans appear to be ahead of their counterparts in other countries in this area as evidenced by some of the work originating from the European Aviation Safety Agency (EASA) and a report from the Aviation Safety Targets for Effective Regulation (ASTER) group.

The ASTER study report, funded by the European Commission, was not focused on UAS integration. It was an attempt to establish a methodology or framework using the TLS approach to analyze the impact of changes to the aviation system. The key facet of this report is the use of a realistic TLS as a starting point and the implementation of a cost-benefit analysis to understand the merits of any proposed safety measures [113]. The general approach of this framework is useful in establishing a pattern to address UAS safety goals.

A book by the aforementioned Dalamagkidis and two of his colleagues that covers UAS integration is an important work for several reasons. One, it provides an excellent reference on existing UAS regulations. Two, it discusses in detail different methods and classification categories that could be used for UAS certification. The book specifically covers details on how to translate a TLS approach into reliability requirements for the UAS. Finally, the book also discusses the risk to people on the ground and details a sensitivity analysis study conducted on this topic [114].

Yet another paper by Weibel and Hansman that looks at UAS integration from a more holistic approach offers useful insight. This paper looks at the entire unmanned aircraft as a system and includes the ground equipment and air traffic system as well. The paper also demonstrates using a basic fault tree method to set up an analytical model of UAS risk. Finally, this paper discusses different techniques for understanding how mitigation steps can be measured in terms of increased or decreased safety levels [115].

An interesting work that, on the surface, is unrelated to UAS integration offers excellent insight into a Quantitative Risk Assessment framework. This PhD thesis from the University of Delft was conducted to assess a methodology for the risk of loss of life due to naturally occurring flooding [116]. What makes this work particularly valuable as a comparison to the current research is that the author, Dr. Jonkman, recognizes that the prediction of such occurrences cannot be accurately tested in a laboratory environment. However, he does use a combination of basic reliability tools such as fault trees, combined with historical data and scientific models to estimate the probability of failures that could cause death, the exposure of the population to such risk and the probability that death will actually occur based on scientific principles.

This approach is very similar to the one required for this framework. To estimate the risk to people's lives due to UAS operations requires a combination of historical reliability data, the prediction of failures and failure rates that could endanger the population, estimates of the exposure of individuals to the risk posed by UAS, and a scientific means to estimate the probability of death due to that exposure.

Another, similar study attempted to estimate the casualties that would occur as a result of an earthquake. The equation used in this study appears below in Equation 3.

$$K_{s_b} = D5_b * [M1_b * M2_b * M3_b * (M4_b * M5_b)]$$

Equation 3

Where b refers to a class of building K_s is the number of expected casualties, D5 is the total number of collapsed buildings, M1 is the population per building, M2 refers to the percent occupancy at time of day, M3 is the number of occupants trapped by a building collapse, M4 is the injury distribution at collapse and M5 accounts for post-collapse mortality [117].

The earthquake study is valuable in developing the eventual UAS safety model for several reasons. One, it readily admits that earthquakes, like UAS accidents, are not something that one can readily test in a controlled environment or replicate to build predictive models. As a result, what is necessary is to build a predictive tool that relies on data and statistics from past events. In addition, it recognizes that disasters consist of a series of events that occur with various probabilities and potential effects on the environment. To that end we see the casualty equation above featuring a multiplicative series of modifiers used to determine the total casualties per event.

Another valuable piece of information from this study was a value for the percentage of expected casualties that occur inside a structure when that structure collapses. The values in this study, which will be discussed in more detail in the modeling section matched very closely with similar values published in a DoD study on explosives damage to structures.

Decision-Making

Ultimately, any integration process for UAS will involve a decision-making process. The literature on decision-making methodologies is extensive and not within the scope of this research. However, a cursory discussion on how the inputs and results of this thesis could affect the decision-making process involved with selecting appropriate UAS integration technologies or procedures is appropriate.

One of the key obstacles to decision making for UAS integration at this time is a lack of knowledge. Because UAS safety and reliability data is primarily within the military domain it is not always publicly available. In addition, it is difficult if not impossible to have complete knowledge of how something as complex as the NAS will be affected by another complex system like UAS until actually integrated. However, it is vital to give decision-makers the necessary information to make informed decisions on the way forward.

An article that discusses decision-making in large-scale public projects discussed the idea of an impact assessment. An impact assessment is a process that can be applied to many different fields that attempts to use a series of steps to aid decision-makers by incrementally understanding the impact of implementing a decision and developing a shared agreement by stakeholders on the nature of the problem [118]. Another term often used to describe this process is Environmental Impact Assessment (EIA) which is defined as "a process having the ultimate objective of providing decision makers with an indication of the likely consequences of their actions" [119]. One particular feature of this approach that makes it applicable to the approach espoused in this paper is that it endorses the use of lower-fidelity tools early in the IA process in order to help decision-makers better understand the problem before committing further resources.

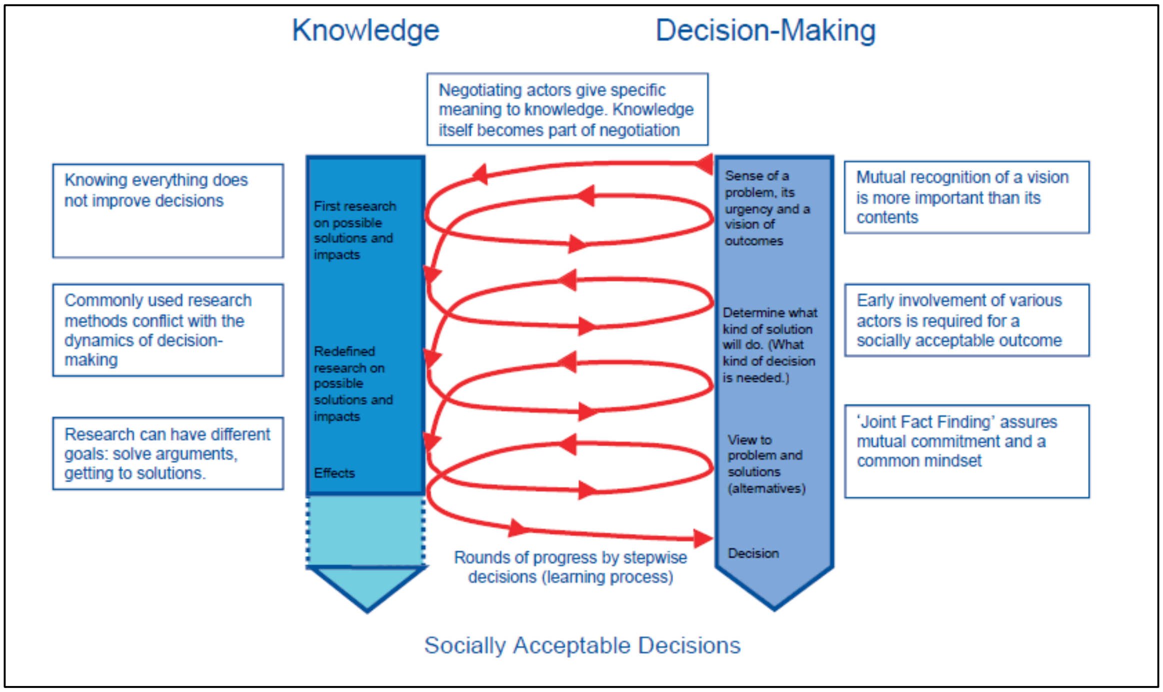


Figure 15: Impact Assessment Diagram [118]

NASA also endorses the use of both qualitative and probabilistic safety tools earlier in the design process to facilitate better decision-making. The diagram below, in a presentation on reliability and safety discusses the need to integrate safety earlier into the design process to make better informed decisions. The modeling and simulation efforts discussed in this research are designed to be simple enough to be used without the need for higher-fidelity, expensive and more time-consuming simulation tools.

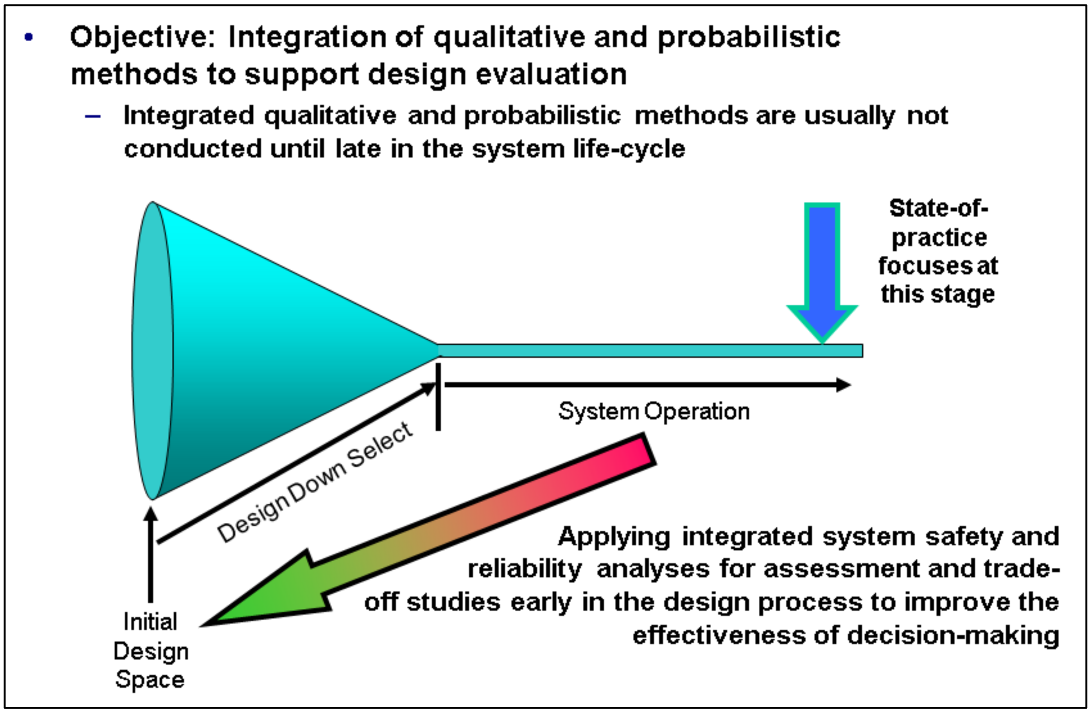


Figure 16: NASA Safety Integration Diagram [120]

Finally, a major consideration in decision-making when it comes to the design of a system usually involves a trade-off analysis. When it comes to integrating UAS into the NAS, multiple trade-offs will have to take place between technological and procedural solutions that take not only safety into account but a myriad of other decisions into account not the least of which is cost. However, the current certification process, based on specified standards for components of the system does not adequately allow for system-level tradeoffs. Currently, if a company wishes to implement a newly-designed system they must demonstrate that it meets an Equivalent Level of Safety (ELOS) to the one it replaces [36] if the manufacturer cannot completely comply with the applicable regulations.

Since there are not enough certification standards to currently cover UAS, an ELOS approach would force UAS designers to comply with manned standards that may not apply. In addition, this one for one approach would not allow designers to conduct tradeoff assessments within the system. With an overall safety target, designers could conduct tradeoffs on sub-systems or individual components to determine the optimal way to achieve the safety target. An ELOS approach does not provide that flexibility.

Summary of State of Literature

While there are several other comprehensive studies in the literature, the works mentioned above offer the best insights into developing an overall safety framework of the kind that will be used in this research. An overview of the current state of the literature on this topic appears below in graphic form in Figure 17. Areas that appear in red are insufficient to address the current problem. Areas in yellow appear in the literature but are marginal in addressing the problem. There are no areas in green that are sufficient to address the problem as outlined above.

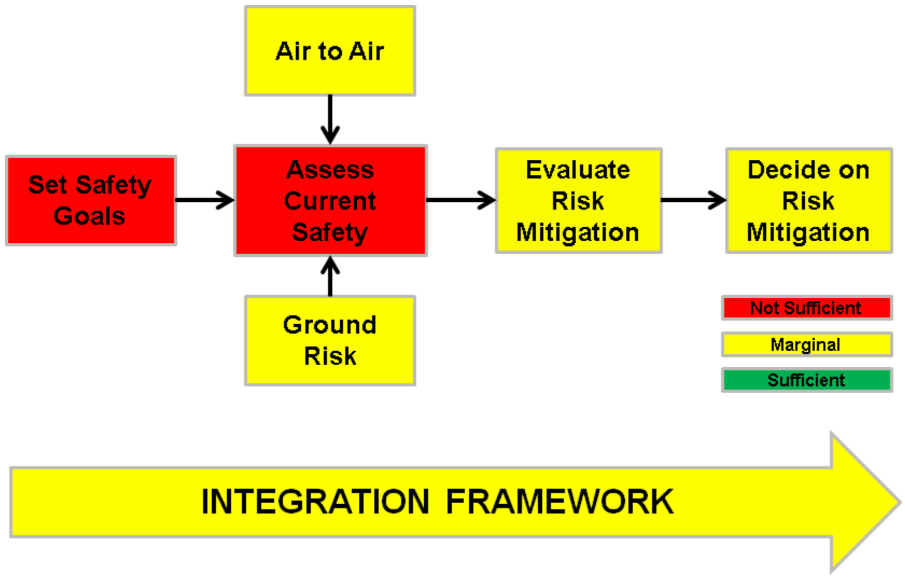


Figure 17: Summary of Literature Review

Overall, there are insufficient sources in the literature on setting specific safety goals for UAS based on the actual risk that UAS pose to society. This lack of information is primarily due to the gap identified in Figure 12. In addition, no one in the literature to date has discussed the impact of choosing different target levels of safety or risk on the reliability or operating requirements of UAS. In the early stages of UAS integration it is crucial to set and understand the realistic impact of safety regulations on the UAS industry.

In terms of the risk from UAS to other users of the airspace, the author believes that there is sufficient information in the literature to accurately predict the frequency of encounters with other airspace users. The basic gas particle models described above have been used for some time to measure encounter probability. However, there is room for improvement to the literature in this area by incorporating information on types of airspace and operating architecture into the air risk model, as well as accounting for the effects of actual air to air collisions in terms of the number of casualties. Finally, avoidance needs to be incorporated into any air risk model.

The literature surrounding UAS risk to people on the ground is marginal. The studies that have been done to date primarily treated the population on the ground as uniformly distributed with no consideration of the actual behavioral patterns of humans. For example, one study on ground risk used the planform area of the air vehicle to estimate the area on the ground impacted by a crash and a simple estimate of the probability of building penetration [91]. Another study used a risk area assumed to be based on the frontal area of the air vehicle and determined by the geometry caused by a glide angle at maximum lift over drag [90]. Another study used some of the sheltering estimates from the Range Commander's Council but made several assumptions about the casualties caused inside a building when a UAV strikes a structure. It also did not account for the clustering of the population inside structures caused by a non-uniform population density [93]. As a result of all of these topics described above, the author estimates that the literature to date on the ground risk was marginal and left room for additional contributions.

The literature is also marginal in assessing an overall risk due to UAS integration. Several of the previous studies analyzed ground risk and midair risk independently but did not put the overall risk together. However, the main area lacking in the literature is the risk posed due to a lost link event. A loss of link can cause both air to air risk and risk to people on the ground, depending on what happens during the lost link event. Lost link is a major concern for UAS integration so not accounting for this risk causes this area to be considered marginal in the literature.

Most of the studies conducted on UAS integration used the techniques outlined in the literature to establish an unmitigated risk level. This is helpful to establish a baseline level of risk or at least compare the worst case risk level. However, it is likely that the most crucial decisions on the UAS integration process will be in terms which mitigation technologies or procedures to implement. Any integration analysis or framework must give the decision maker the ability to analyze the impact of mitigation measures on safety levels. While there are many generic optimization tools available, there is little in the literature with data on the impact of implementing SAA technology, ground impact attenuation, or any other currently proposed risk mitigation measures. Therefore, this topic is assessed to be marginal as well. This area is marginal instead of unsatisfactory because there is information in the literature on mitigation measures outside of the UAS literature.

For example, there are several studies that discuss the effectiveness of ADS-B in detecting other aircraft [121]. There are studies on other sense and avoid technologies as well [122]. The literature has several studies on the effectiveness of TCAS on aircraft [71, 101, 123]. There is information regarding the use of a parachute on Cirrus general aviation aircraft which could be used to assess impact attenuation for UAS [124]. There are also several studies on the ability of a pilot to visually detect other aircraft which could be used to determine the ability of pilots in manned aircraft to detect UAS [125-127].

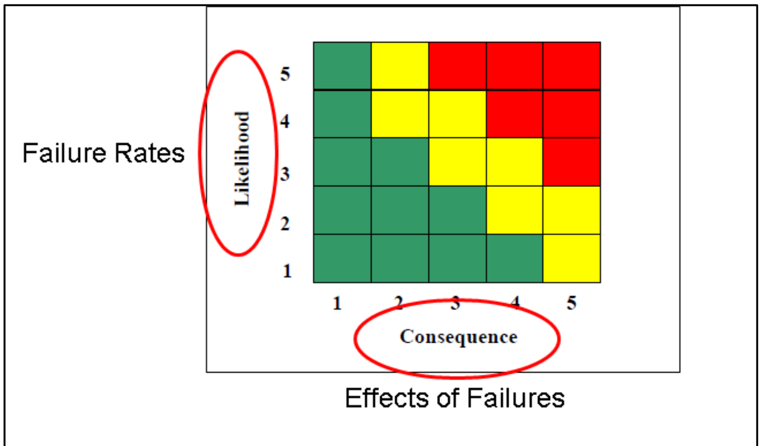
Finally, in terms of decision-making to determine the optimal combination of mitigation measures, the literature again is marginal. This area is assessed as marginal only because the literature is extremely abundant in overall decision-making techniques.

However, with the lack of an overall UAS integration framework, there is nothing in the literature that shows how the decision-making process could be used for this problem.

RESEARCH

It is the premise of this thesis that the overall problem inhibiting full UAS integration is the lack of agreed-upon safety goals or targets to govern UAS integration and certification. In other words, how safe is safe enough for UAS integration? The secondary problem that follows from the first is if safety goals were established, there is still no accepted method to predict UAS safety levels because of the lack of connection between UAS hazards and consequences.

Without a way to predict risk that can take casualties outside the UAS into account, there is no way to effectively link UAS safety to reliability and operating environment. In other words, how safe are UAS to the public and other NAS users. Referring again to the typical risk assessment matrix in Figure 18, the gap that must be closed covers the effects of UAS failures. While several studies have attempted to quantify UAS risk, as discussed in the literature review, most have relied on general assumptions to account for things such as impact area, shelter effects and population density for ground risk. For midair risk, the studies have used existing tools to quantify the risk of NMAC but not analyzed the impact of airspace, mitigation measures, and avoidance rates on casualty rates.



$$\frac{Casualties}{Time} = \frac{Failures}{Time} * P\left(\frac{Casualty}{Failure}\right)$$

Figure 18: The UAS Safety Knowledge Gap

Overall, a method to predict casualties caused by UAS operations is required. While there are other metrics that could be used to assess UAS integration such as the economic impact of UAS failures, or injuries, the fatality rate was chosen as the metric for this research for several reasons. One, it is generally considered the most important aspect of safety and therefore should be considered before any other metrics are used [128]. Second, data and information to predict fatalities was difficult enough to obtain. The requirements to determine economic risk would be more difficult to obtain and more open to interpretation and were therefore beyond the scope of this effort. More importantly, using the fatality per hour metric aligned this research with several other safety methods to include the aforementioned Range Commander's Council and Nuclear Regulatory Commission. Finally, the primary concern of the FAA is public safety, not necessarily property damage or economic impact. Therefore, fatalities were selected as the metric of choice.

This method should incorporate tools and methods that focus on internal risk such as manned aviation (Failure Modes and Effects Analysis, Fault Trees) and external risk such as the RCC and NRC (Event Trees, Terminal Effects). Only when safety can be linked to reliability and operating environment can decisions on proper UAS integration be made. It is the 'gap' between UAS failures and their effects that needs to be addressed to move integration efforts forward. If this 'gap' can be closed then several things can occur:

1. Regulations that cover reliability standards and operating restrictions can be linked to safety levels.
2. UAS designers will have reliability targets for their designs that are based on safety levels.
3. Effectiveness standards for mitigation measures such as Sense and Avoid can be developed that are linked directly to safety levels.

In contrast to the use of fatalities per hour as a metric, two other potential approaches are discussed. As mentioned above, another approach could be to use a cost estimate of the damage that UAS operations cause. In this approach, the loss of human life can also be assessed as a monetary value [129, 130], and those values can be compared or added to the monetary damage to property. However, there are two problems with the use of this approach. One, the primary concern of the FAA, as mentioned above, is public safety. This translates to a concern with protecting people and not necessarily preventing damage that exceeds a specified monetary amount. Second, the information required to population a property damage prediction tool would be well beyond the scope of this thesis. Predicting economic impact would require more detailed estimates of the amount of damage to property that a UAS crash could cause, requiring monetary estimates of the damage. These values would clearly differ depending on the part of the country and even depending on the type of neighborhood the crash occurred. For example, damage to a large home in California would cost more to repair than a smaller residence in the Midwest, on average. Thus, any monetary damage estimates would significantly increase the complexity of the prediction model for no particular benefit, since all of the relevant stakeholders are primarily concerned with hazards to humans.

Another potential concern is the secondary damage caused by UAS crashes. For example, if a UAS impacts a chemical plant or a fuel storage area, there is the potential to cause damage well beyond what the UAS impact could cause alone. However, to include the concept of secondary damage into a prediction tool in this research would be prohibitive. First, the intent of this research was to analyze UAS operations on a more general, or statistical level. To determine the probability of impacting an area that could cause a high degree of secondary damage would require a much more detailed analysis of the particular ground area in question. Furthermore, such an effort would also require much more detailed analysis to predict the potential outcomes of a UAS crash into such an area. Again, while the idea of secondary damage is potentially a concern for UAS operations, predicting the outcomes of such incidents was simply not feasible in this thesis. In addition, an analysis of this kind would be inconsistent with operations of manned aircraft already in place. There are no requirements in the Code of Federal Regulations, Title 14 that prohibit aircraft from flying over chemical plants or fuel storage areas, for example, other than the altitude restrictions that apply in all areas outlined in 14 CFR Part 91.

The specific research objectives, questions and hypotheses are discussed in the sections. In order to address the fundamental problems stated above, a framework needed to be developed that could accurately predict casualties caused by UAS operations. The development of this framework is addressed in Part 1 below. In addition, one of the aims of this research was to explore the implications of being able to predict casualty rates in terms of the risk posed by UAS operations in the near future. This area is addressed in Part 2. Finally, this thesis demonstrated potential applications for the framework in terms of UAS certification and the development of mitigation techniques in Part 3.

Part 1: Develop a Framework

Objective 1: Develop a framework that can accurately predict casualties caused by UAS operations. The framework should be transparent, repeatable, flexible, and capable of incorporating results from more sophisticated tools or studies.

Objective 1a: Accomplish this objective using readily available software tools to demonstrate the applicability of this approach.

Objective 1b: Accomplish this objective using supporting data that is already approved or validated to reinforce credibility of effort.

Research Question 1: Can reliability tools and data from existing studies be used to develop a casualty prediction framework for UAS operations that takes into account:

- UAS characteristics
    - Size, weight, speed, system failure rate, link failure rate
- Operating environment
    - Population density, airspace density, types of buildings
- Architecture
    - Controlled vs. uncontrolled airspace, IFR vs VFR traffic, autonomous vs fully controlled operation
- Mitigation
    - Sense and avoid, crash attenuation, lost link behavior

Hypothesis 1: UAS safety levels can be predicted from failure rates to within an order of magnitude.

- To do this an experiment must be developed to determine if casualties can be predicted based on system failure rates and operating environment
    - The experiment will use manned aircraft characteristics, accident data, and bystander casualty data to validate the experiment
    - The primary metric will be how close can the framework predict estimated casualties (E_c) when compared to historical data (% Difference)

A secondary goal in part 1 is to conduct a sensitivity analysis on the experiment to determine key parameters that drive casualty predictions the in framework in order to:

- Determine the effects of human behavior patterns vs. uniform population for population density parameter
- Determine the effects of incorporating shelter into framework
- Determine the effects of incorporating different methods of predicting impact area of accident

Part 2: Implications of the Framework

If a capability for casualty prediction can be developed, then contributions to the literature on this topic can be advanced by exploring the impacts of policy decisions on safety levels, required reliability levels, and allowable operating environment.

Objective 2: Using the casualty prediction tool, demonstrate the implications for integration stakeholder decision-makers.

Research Question 2a:

What level of safety would UAS of specified sizes in various operating environments achieve, based on current statistical failure rate levels?

Hypothesis 2a:

UAS at the 4.4 Lb and 55 Lb sizes identified in the 2012 FAA Modernization Act can already meet or exceed manned aircraft casualty rates at current failure rate levels due to their relatively low probability of causing a casualty.

Research Question 2b: What effect on UAS safety levels does requiring UAS to meet manned aircraft failure rates have? In other words, if the default position of stakeholders is to hold UAS to the same failure rate standards as manned aircraft, would UAS be more or less safe than manned aircraft. Essentially, this is a case of fixing the failure rate at the center of the bow-tie diagram and using the event trees to determine the resulting casualty rates on the right side of the bow-tie diagram after crossing the gap, as depicted in Figure 12.

Hypothesis 2b: Requiring all UAS to attain the same system failure rates as manned aircraft ($1x10^{-6}$ to $1x10^{-9}$) would penalize UAS designers and operators by indirectly requiring safety levels two or more orders of magnitude better than current manned aircraft safety levels.

Research Question 2.c: What is the impact of mandating specified target levels of safety have on allowable UAS failure rate levels and operating environments? Although this research question sounds similar to the one in 2.b., it is slightly different. In question 2.c., the system failure rates at the center of the bow-tie diagram are set based on current UAS failure data. The casualty rates on the far right side of the bow-tie diagram are set in the form of TLS values and the impact of changing those values is measured based on what percentage of UAS and environment combinations are allowed for each TLS.

Hypothesis 2c: Mandating TLS levels more stringent than historical manned aircraft will unnecessarily restrict UAS operations or require reliability levels two or more orders of magnitude better than current, demonstrated UAS failure rate levels.

Part 3: Applications of the Framework

Without a stated safety target and a framework to predict or test UAS safety levels, stakeholders have no maximum failure rate or minimum effectiveness targets to guide the design of UAS, UAS sub-systems or mitigation measures.

Objective 3: Demonstrate the use of the UAS Integration framework to determine minimum requirements for UAS sub-systems or mitigation effectiveness. This will be demonstrated by applying the framework to three case studies which will include a remote border patrol mission, a suburban disaster response mission and an urban law enforcement mission. In addition, recommended standards for failure rate and effectiveness will be discussed in the context of a certification scheme.

Research Question 3.a What is the maximum air vehicle sub-system failure rate allowed that still meets a required TLS?

Research Question 3.b What is the maximum link sub-system failure rate of the system that still meets a required TLS?

Research Question 3.c What is the minimum sense and avoid sub-system effectiveness that still meets a required TLS?

Research Question 3.d How effective would a method to attenuate crash impact on the ground have on meeting system TLS?

Having established specific research objectives and questions, the author had three additional reasons for conducting this research. The first was to establish a dialogue and archive a discussion on the proposed acceptable TLS for UAS operations. Second, the author wished to expand the estimates of how safe UAS operations can be. To accomplish these goals, one had to expand the research into the realistic risk that UAS operations pose to bystanders on the ground and the estimates of risk due to midair collisions. This will serve as a safety benchmark that future research can expand upon.

Third, the author wished to conduct this analysis using simple, commonly available tools to demonstrate that this analysis can be done by the operational stakeholders without expensive software or M&S tools that are difficult to share. This will also allow other researchers in the field to quickly expand upon the analysis tools.

RESULTS AND DISCUSSION

As described in the Research section, this thesis was developed in three parts. Each part will be discussed separately in the Results and Discussion section. For each part, a description of the process required to develop that part will be discussed first. Then the results of that part will be described in detail and analyzed. When applicable, the research questions and hypotheses will be addressed as well.

Part 1: Develop a Framework

To accomplish all the goals of this thesis and address the research objectives and questions, a framework was required to guide the process. This framework can create a starting point for further analysis into acceptable UAS risk, certification procedures, SAA technology, UAS concept of operations, protection from risk due to shelter, and decision support tools. A graphical depiction of the framework appears in Figure 19. First, based on the literature review, it consists of an overall Target Level of Safety approach to the problem. The use of this approach was based on the previously discussed desires of many stakeholders to avoid a certification process that relied on the extensive use of standards, and the recognition of the fact that UAS reliability is not necessarily linked to safety, unless the environment in which UAS operate in is considered.

However, to apply a TLS approach to this problem requires a means to predict UAS casualties. To accomplish this end, the event tree format was used based on the advantages of this tool previously discussed. Finally, a process to link the results of the event trees and the TLS approach was needed. That process, known as SAfE-D, was developed to bridge the TLS approach and event tree format.

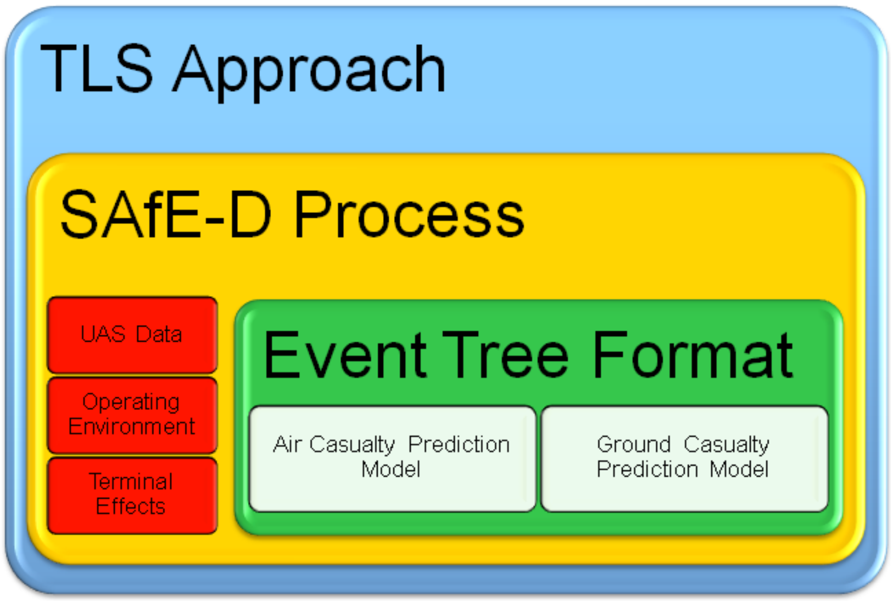


Figure 19: Depiction of Framework

The SAfE-D process was designed to demonstrate how the stakeholders in this process could use the tools developed in the first two steps to drive the integration process. The steps in the process are described in more detail below.

Figure 20: SAfE-D Steps

<u>S</u>et a TLS

In this step, one of the target levels of safety from Part 2 was utilized to demonstrate how this step creates the requirements necessary for the rest of the process to proceed.

<u>A</u>ssess Safety levels and <u>f</u>ilter Cases

In this step, mission scenarios were evaluated using the models developed in Part 1. The purpose of the filter sub-step was to determine if there are cases that meet the system TLS. In other words, can the UAS with current reliability levels meet the TLS with a specified confidence level? The combination of system and environmental parameters that do not meet the goal TLS were carried forward to the next step.

<u>E</u>valuate Mitigation Measures

Any scenarios that did not meet the TLS with confidence would require risk mitigation measures before full integration can take place. The purpose of this step was to demonstrate how the framework could help analyze the appropriate mitigation measures, depending on why the scenario did not meet the goal TLS. For example, if the scenario exceeded goal TLS because of midair collisions, then a more capable method of avoiding collisions is necessary. As a result, a SAA system could be added to the model or greater controls on the air environment could be put in place.

For example, one risk mitigation measure that has probably received the most attention with regard to UAS integration is Sense and Avoid (SAA) to replace the pilot's ability to see and avoid other aircraft in accordance with Federal Aviation Regulation 91.113. Several entities to include the United States Army and Air Force have conducted testing on SAA systems. A quote from a contractor involved in SAA system development in an article on testing mentioned that the testing his company was conducting would help the "future development of performance standards" [131].

However, the development of such a system under a TLS approach would require effectiveness standards instead of simply performance standards. Effectiveness standards combine both performance and reliability standards into one metric that determines how effectiveness the system is in achieving a desired goal, in this case avoiding collisions. With the TLS approach, the effectiveness standard can be set to reduce the assessed risk levels to appropriate values.

Decide

Ultimately, this process would require a decision on the most appropriate mitigation measure, depending on customer requirements and constraints. The author will discuss the decision-making step in the context of this problem and show how the results of Step 4, can be used to aid decision-makers. However, it is important to note that the purpose of this research was not to describe in detail any decision-making techniques or demonstrate a decision process for UAS integration. The literature on decision making in engineering and in general is already extremely robust. In addition, much of the input required to conduct a multi-attribute decision-making exercise is not available at this time. An example of the additional information required to conduct a more comprehensive decision-making process would be the cost of a particular risk mitigation measure or the cost to the industry of more restricted operating requirements implemented to offset risk.

There are several examples throughout Part 3 of this effort that could be used to help support decision-makers in this process. For example, there is a discussion of the use of an impact mitigation device such as a parachute and a demonstration of the effect that including this type of device in the model has on the casualty rate. There is also a comparison of the casualty rate under lost link conditions using a ground-based sense and avoid system compared to an air-based system. When this safety data is combined with further information such as cost, weight and technology readiness, stakeholders would have a clearer picture on how to decide on how to implement such systems.

Modeling and Simulation

In order to properly answer the research questions posed for Part 1, an experiment was needed. The key was to determine whether it is possible to accurately predict third-party casualties caused by UAS operations using existing data and studies. Based on the importance of this topic, the implications for public safety, and the need for agreement from multiple stakeholders, the prediction tool should have several criteria. First, the prediction tool must be transparent and easy to understand so that any stakeholder can investigate the results. Second, the tool should be adaptable enough to allow input from future studies to improve accuracy and fidelity as the data becomes available. Third, the tool needs to be flexible in nature so that stakeholders can analyze safety for a variety of different scenarios to include operating environments and mitigation measures. Finally, and perhaps most important, the prediction tool needs to be credible. This last criterion was a critical driver throughout the process in choosing input data and supporting information that was already credible. A list of the criteria for this tool appears below:

1. Transparent
2. Adaptable
3. Flexible
4. Credible

The National Airspace System is an exceedingly complex system and any attempt to model all aspect of this system would require a massive effort. However, several sources on this subject recommend the use of an Event Tree model format in order to predict the casualties caused by UAS in the NAS and their interaction with the environment. Event trees are established tools that can be used to determine the probability and impact of specified failure events. They were originally detailed in a 1975 report by the Nuclear Regulatory Commission but later used in many other applications. Event Trees are usually used in conjunction with fault trees in reliability and safety studies. Fault trees trace a fault backwards to determine the root cause while an event tree traces that fault or event forward to determine its outcome or outcomes [132].

In the context of this research, the use of event trees allowed for the estimation of fatalities caused by failures of the UAS or breakdowns in the NAS. It was beyond the scope of this problem to trace those failures all the way to their root cause since that would involve detailed investigation of the sub-systems and components of a particular UAS or type of UAS. However, it is important to note that this research demonstrated how the event trees can be used to determine failure thresholds or limits that can be applied in reverse to drive the fault tree process prevalent in System Safety Assessments.

Event trees appear in the literature for risk and safety assessments after they were first used in a study to predict the risk due to nuclear power plants. NASA's guide to risk assessment discusses both Event Sequence Diagrams (ESD) and Event Trees (ET). An example of each diagram appears in Figure 21 and Figure 22.

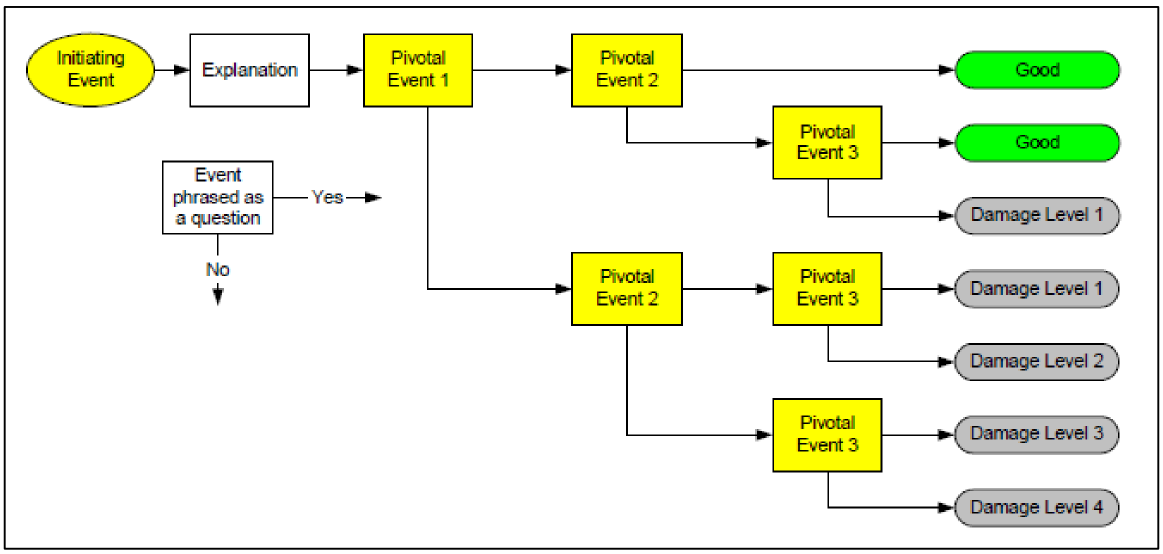


Figure 21: Example Event Sequence Diagram [23]

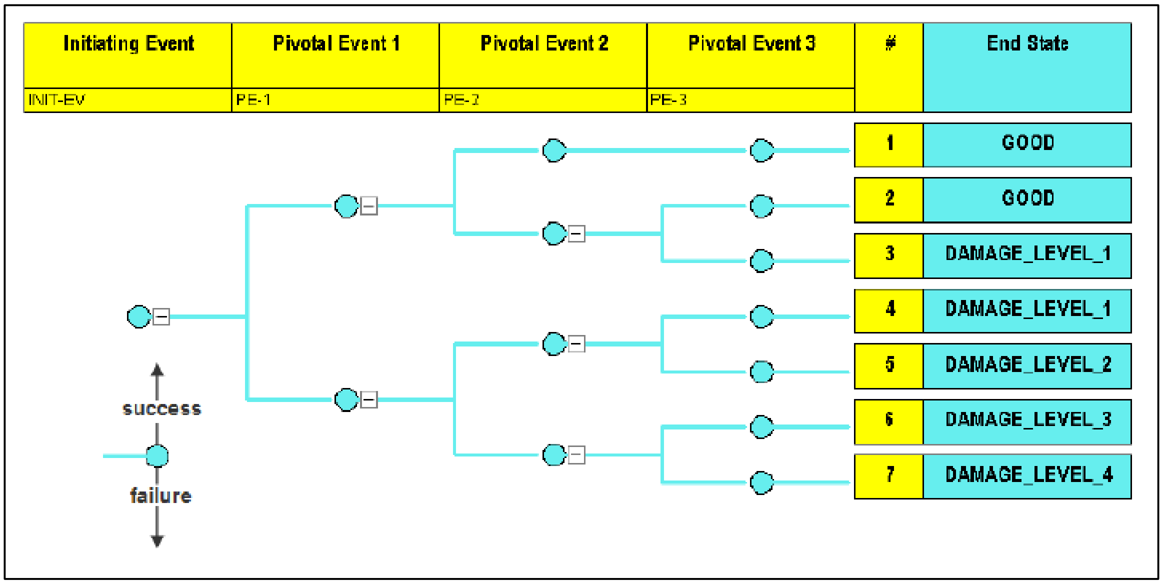


Figure 22: Example Event Tree [23]

Although there are slight differences used in the logic between these two techniques, both demonstrate a technique to capture a series of events that lead to different outcomes. The NASA guide highlights the advantages of these techniques in that they lend themselves to quantitative methods of risk estimation and also serve as a communication tool as well as a modeling tool [23]. Because of the logical flow of these tools, they can assist decision-makers in communicating the effects of specific events. Most importantly, is that the very process of creating the event trees is a safety tool by itself. By forcing the user to explore the logical events and their interactions that can cause hazards, this exercise is part of the entire safety assessment process even before the tool is used with quantitative methods. Another advantage of event tree analysis, as cited by a multi-organizational guide to air traffic control tools, is that event trees can help explore the impact of not only faults in a system but normal operating states that can also generate hazards [133].

The relative simplicity of ETs is in contrast to more advanced simulations or modeling techniques. One problem that other more advanced simulation tools have when trying to assess the safety level of something like the NAS is that it is difficult to obtain results for events that occur so infrequently. Blom, in an article on safety assessment for midair collisions and air traffic management points out that in order to properly understand the impact of accidents that may only occur on the order of every 10^{-8} flight hours would require simulations that replicate over 10^{9} flight hours and the appropriate fault initiating events [134]. To conduct this type of analysis with an agent-based model or another more complex simulation would be both time and cost prohibitive.

Conceptually, the event trees created for this framework followed a common structure. They begin with an initiating event (IE). The generic IE can be either a system failure that would prohibit the UAS from continued safe flight, a condition caused by lost link, or an encounter with another airspace user. Next, it is important to examine the operating environments in which the IE can take place. The environment determines both the number of bystanders exposed to risk as well as the context in which that risk takes place. For example, an encounter that occurs under Visual Meteorological Conditions (VMC) conditions has different implications for safety than one that takes place in Instrument Meteorological Conditions (IMC).   The NLR study refers to the three elements of third party risk assessment as failure probability, failure location, and failure consequences [79].

Next, in later phases of the research a layer of mitigation was added to the ETs to examine the potential effects of placing risk mitigation measures into the architecture or on the UAS itself. Finally, the terminal effects of the initiating event were examined to determine the number of casualties expected for each IE. These effects were examined based on both the operating environment and the characteristics of the UAS. A conceptual diagram that shows the major components of the ETs appears in Figure 23.

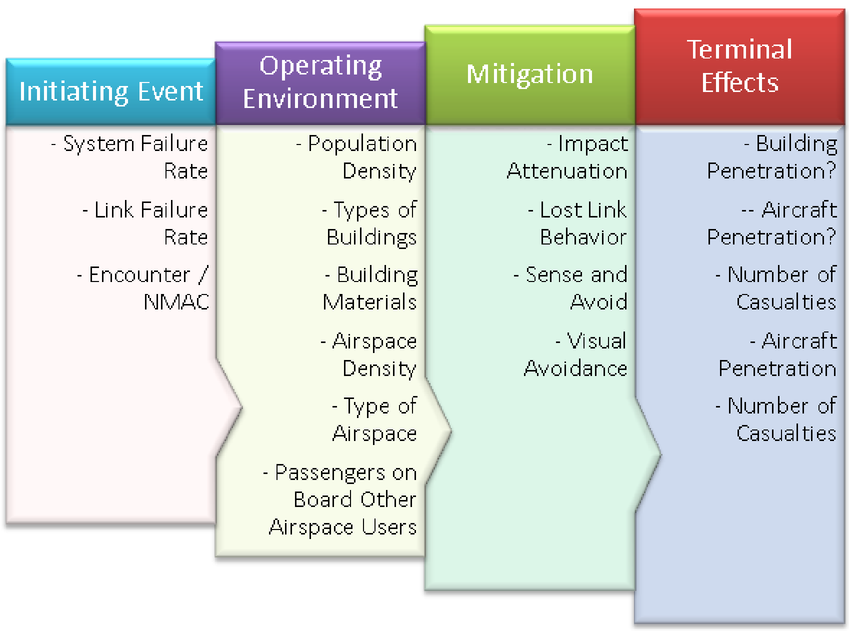


Figure 23: Event Tree Structure

A schematic of the modeling process appears below in Figure 24. The major components of the model are the UAS, the Air Environment, the Ground Environment and the Concept of Operation or how UAS are allowed to operate in the NAS. Information to populate the model will come from a variety of primary sources and previous studies. A list of the more critical information to populate the model appears in Table 6.

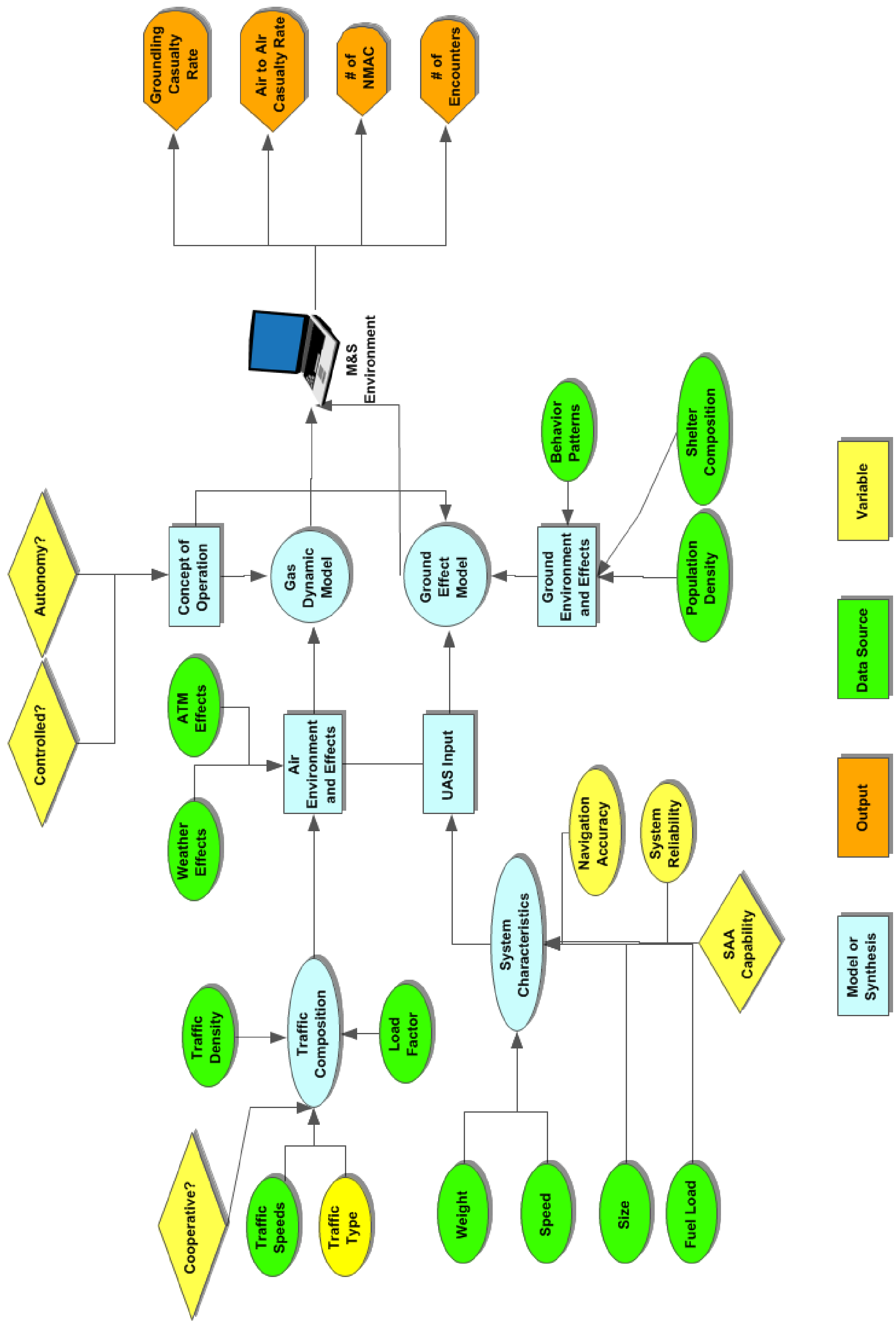


Figure 24: Modeling Process

Table 6: Model Parameters and Sources

Model Parameter	Source	Type	Citation
UAS Input			
Weight	Survey of Vehicles	Distribution	[135]
Speed	Regression Based on Weight	Equation	[136]
Size	Regression Based on Weight	Equation	[135]
Fuel Load	Regression Based on Weight	Equation	[137]
Air Vehicle Reliability	Failure Rate	Value/Variable	[4, 50, 138]
Link Reliability	Failure Rate	Value/Variable	[4, 138]
Navigation Accuracy	Based on ADS-B Requirements	Value	[139]
Collision Avoidance Effectiveness	Various Studies	Equation / Value	[101, 140, 141]
Air Environment and Effects			
Traffic Speeds	Average of Radar Reports	Distribution	[141, 142]
Traffic Composition	FAA Statistics	Values	[141, 142]
Traffic Density	Average of Radar Reports	Variable	[142]
Load Factor	FAA Statistics	Distribution	[143]
Weather Effects	Incident Statistics	Value	[144, 145]
ATM Effects	Incident Statistics	Value	[146]
Type of Airspace	Controlled vs. Uncontrolled	Decision	N/A
Ground Environment and Effects			
Population Density	Census Data	Distribution	[93, 147]
Behavior Patterns	NHAPS Study	Variable	[148]
Shelter Composition and Effects	Various	Equations	[75, 96, 107-109, 111, 149-151]
Concept of Operation			
Level of Autonomy	Autonomous vs. Guided	Decision	N/A
Lost Link Behavior	Loiter or Return	Decision	N/A
SAA Type	Ground or Air Based	Decision	[104, 122]

In order to accurately represent various UAS that could operate in the NAS required an analysis of a variety of current UAS. The key parameters required for this entire research were weight, speed, wingspan, fuel load and endurance. The weight and fuel load were required for kinetic and chemical energy as discussed in the ground risk event tree and wingspan and speed were required for the air risk event tree. Endurance was used later in the lost link event tree.

Based on research of current UAS, it was possible to develop a distribution to represent UAS weights. From existing data on UAS it was also possible to determine a relationship between UAS weights and the other four parameters just discussed. The relationships used in the model to represent likely UAS appear in Table 7.

.

Table 7: UAS Parameters for Model

Information	Value	Units	Source	Citation
UAS Weights	*Lognormal:* Mean: 2582.44 Std Dev: 20,994.3	lbs	Survey of Vehicles	[135]
Speed	88.18 + 0.0279 * Weight	ft / s	Regression Based on Weight	[136]
Wingspan	12.015368 + 0.0140653 * Weight – 4.6313e-7 * $(Weight-1807.6)^2$	ft		[135]
Fuel Load	-42.1565 + 0.5073 * Weight	lbs		[137]
Endurance	6.0627732 + 0.0079073 * Weight – 8.0357e-7 * $(Weight -1495.18)^2$	hrs		[4, 137]

To conduct the analysis required for this research, a software tool was required that could perform several functions. First, the tool needed to be able to incorporate a probabilistic method to account for the uncertainty present in the effects UAS would have on the environment and model the range of values inherent in many of the parameters related to the problem. In addition, it was desirable to have a tool that could integrate the Event Tree format visually in order to facilitate the analysis of the events and impact associated with UAS failures.

Beyond the above stated requirements, it was desirable to have a software tool that was readily available to a wide range of users, was inexpensive, and could integrate with the software tools or packages that most analysts and decision makers already use. Based on these criteria, a tool that could integrate with Microsoft Excel™ was preferable.

To meet all of the above criteria, two software packages were identified and evaluated. The first was Crystal Ball™, available from Oracle. Another package was

@Risk™, which is one part of the Decision Tools suite from Palisade, Inc. Both are add-in packages to MS Excel™ and offer user-friendly methods to replace deterministic cells in a spreadsheet with a wide range of probability distributions. Both tools also allow users to conduct simulations replacing the cells with random selections based on the probability distributions selected. Both packages offer additional features to include sensitivity analysis designed to determine the impact of input variables in the model on the model output, distribution-fitting tools and scenario analysis.

After conducting initial evaluations of both software packages, there was no significant difference in the capabilities of the baseline Monte Carlo simulation features of both software packages. However, the Decision Tools suite by Palisade also offered a decision analysis tool that featured a graphic decision tree format as well. This tool could be integrated directly with the simulation tool @Risk™. Based on this additional feature, the author decided to use the Decision Tools suite for this research.

As mentioned previously, @Risk™ allows the user to replace cells in an Excel spreadsheet with the important parameters for a wide range of available probability distributions. This approach allows the analyst to use a technique known as Monte Carlo simulation. It is not the author's intent to explain Monte Carlo simulation in great detail in this paper as there is ample information available on the subject. Many phenomena in science and engineering cannot be adequately described by a deterministic value. One way to overcome that challenge is to use a pseudo-random value selected from a probability distribution set by the user [152]. That distribution is sampled thousands of times in the context of a model to generate a range of output variables. This technique is known as Monte Carlo simulation.

The @Risk™ software offers the use of 37 different probability distributions. However, for the purpose of this research only a few select distributions were required. It is also of note that the software uses the Mersenne Twister random number generator [153] for Monte Carlo simulations. This method is known to be meet statistical tests for randomness while retaining the speed of the generation process to avoid making any simulation unnecessarily cumbersome [154].

The first step in developing the quantitative models required for this analysis it was necessary to develop the logic of the Event Trees that captured the possible outcomes of UAS failures. Referring to Figure 25 below, the focus of the Event Tree analysis conducted is the right side of the diagram, outlined in red.

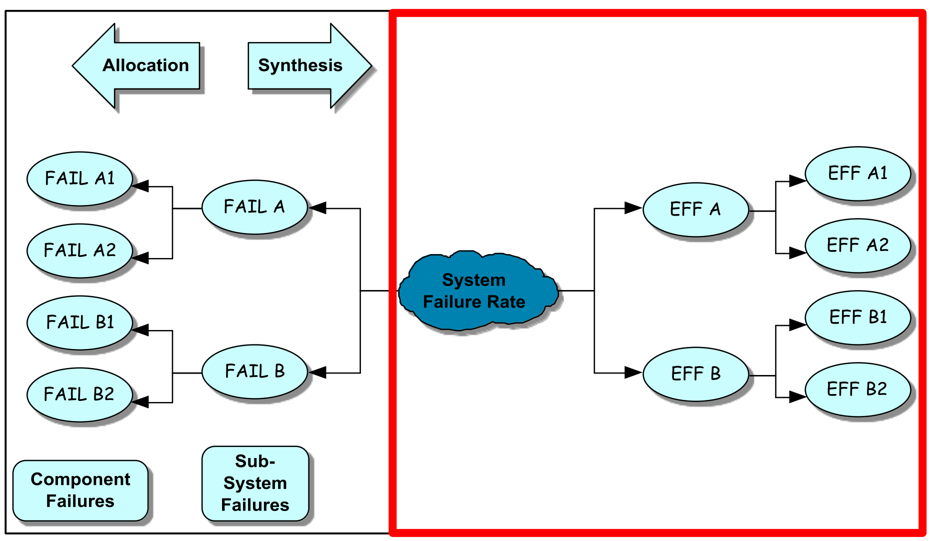


Figure 25: Event Tree Focus

It was not the intent of this research to analyze the specific causes for UAS failures. The literature on reliability analysis to include Fault Trees and other methods is well-established. Any in-depth analysis on this aspect of the problem, which would coincide with the left side of the diagram in Figure 25, would also become more focused on a particular type or family of UAS which was beyond the scope of this effort. The RCC supplement on UAS risk features several examples of the types of failures that would contribute to the overall system failure. An example of one of these lists appears in Figure 26.

Hazardous condition	Cause
Loss of propulsion	• engine failure • fuel starvation • stuck throttle • icing / weather
Loss of lift	• structural failure • icing / weather
Loss of heading / attitude / position information	• heading / attitude system failure • navigation system failure
Unplanned loss of link	• radio frequency interference • flight beyond horizon • antenna masking • loss of ground control station • software interrupt between ground control station and air vehicle • atmospheric attenuation • inadvertent deactivation of autopilot • loss of satellite link
Loss of control surface performance	• stuck servo • autopilot failure • icing / damage to control surface
Loss of UAV electrical power	• generator failure • backup battery failure • excessive load from payload
Loss of ground control station (GCS)	• Loss of GCS power • GCS transmitter/ receiver / antenna failure • GCS computer failure

Figure 26: Conditions That Could Contribute to Uncontrolled Flight [39]

Despite not concentrating on specific UAS component failures, it was necessary to identify broad classes of failure. In this particular case, the important aspects considered were overall system failure and link failure. System failure refers to the collection of failures that would cause the UAS to be unable to sustain continued flight.

Examples would be propulsion failures, control system failures and certain material failures. Failures that fall into these categories were summarized as a system failure rate in units of failure per 100,000 flight hours.

Lost link failures could occur anywhere along the chain that allows control from the operator to the air vehicle itself. This could include the ground station, data transmission mode, or the transmitter / receiver on the air vehicle. Later as mitigation technologies are added to the model, their reliability will be accounted for in conjunction with an effectiveness metric. Instead of a failure rate, effectiveness will be measured in terms of the percent likelihood that the mitigation tool will perform its intended task. The effectiveness can be degraded by a lack of reliability or a lack of design features that allow the measure to achieve a task. For example, a system intended to avoid MACs that somehow manages to avoid 100% of collisions, but is in a failed state 25% of the time would only be 75% effective. In contrast, a system that had 100% reliability but was only designed to avoid 75% of potential MACs would also be 75% effective.

Information about the UAS was mainly determined from data on existing UAS with some reliability data based on projections of future failure rates. The Air Environment is a complex one, but one that has been studied in some detail in previous studies. The overall model for the air to air risk was a gas dynamic model, which treats the UAS and other aircraft in the NAS as random particles in space.

Three primary models were developed for this analysis using the event tree format. The first accounted for risk for bystanders as a result of UAS system failures. The second accounted for the risk to other airspace users due to midair collisions with

UAS. The third event tree created the logic to account for lost link events that could cause either a midair collision or a ground event.

A key aspect of creating a casualty prediction tool or method is the choice of data and information to populate the tool. Past studies have differed in their selection of critical input parameters to their prediction methods. While each of these data sources will be explained in much more detail throughout the Results and Discussion section, Table 8 is a summary of the input sources and methods of several of the major UAS integration studies and a comparison to the input sources used in this thesis. This table serves as a basis for comparison to provide a preliminary understanding of how this research differs from past efforts.

Table 8: Overall Model Parameter Comparisons

Model Parameter	Clothier	Waggoner	Burke	Dalamagkidis	Weibel	Current Thesis
Ground Risk Model	Uniform Pop., Geometry -Based Impact Area and No Shelter	Uniform Pop., Geometry-Based Impact and No Shelter	Uniform Pop., Geometry-Based Impact and Shelter Linked to Pop. Density	Uniform Pop., Geometry-Based Impact Area and Shelter Incorporated into Casualty Estimation	Uniform Pop., Geometry-Based Impact and Shelter Estimate Based on Vehicle Size	Event Tree Format with Non-Uniform Population Shelter Effects and Mitigation
Air Risk Model	N/A	Gas Model with Derived Avoidance and Passenger Estimates	N/A	Gas Model	Gas Model with Airway Analysis	Gas Model with Avoidance Study Data Airspace Analysis and Casualty Effects Data
Lost Link Model	N/A					Linked to Ground and Air Risk Models with Mitigation Logic Incorporated
Validation Offered	No	Air Model	No	No	No	With GA and Air Carrier Historical Data

One of the most critical steps in developing the air and ground risk models was to ensure that they were relevant and able to predict the risk that UAS posed. However, this was not a straightforward task since there is insufficient data on UAS incidents and fatalities to use in any validation effort. Despite the difficulty in validating a model against UAS data, this step is extremely important before conducting any analysis using the models.

Validation can be defined as "the process of determining the manner and degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model, and of establishing the level of confidence that should be placed on this assessment" [155]. The key points in this definition are that the model should accurately represent the real world and it should establish confidence that it is useful for its intended purpose.

Barlas [156], in an article on validation of system dynamic models, discusses two points relevant to this discussion. One, he mentions that establishing strict numerical criteria for the validation of a dynamic model is often difficult because the data required to build a model can be highly correlated and there may not be a null hypothesis to verify. He also mentions that, in addition to verifying that the model provides results that meet a need, a model should be internally validated to ensure that the pieces that make up the whole are valid. To the extent possible, the data used to populate the models in this effort was reviewed separately to ensure that it was useful in predicting the individual purpose before being incorporated into the larger model. For example, the Ale and Piers [96] data for predicting impact area based on aircraft maximum takeoff weight, was reviewed by comparing the prediction to several actual aircraft crash reports. When validation in this manner was not possible, as was the case for the level of protection afforded by different construction materials, the data was compared to other sources to gain greater confidence in its veracity. Finally, if a comparison was not possible, the data used to populate aspects of the model was taken from reliable sources such as the DoD or NASA. These steps follow the early discussion of the criteria used to shape the model, specifically the credible criterion.

To truly validate the model though would require real UAS fatality data to compare against and at this time this is simply not available. Instead, the author decided to use manned aircraft mishaps and bystander casualty data to determine the validity of the model.

In order to better understand the key factors that contribute to the uncertainty and variability in the results of the model, a sensitivity analysis of each of the models was conducted. The @Risk software features sensitivity analysis tools, the easiest of which to interpret are tornado graphs. These graphs were used to show the regression coefficients between input variables to the model and selected output or response variables. The tornado graph depicts the input variables in rank order from top to bottom, based on which input variable had the largest effect on the variability of the output. The values displayed in the standard regression coefficient tornado ploy are normalized regression coefficients. For example, a value of one indicates that a one standard deviation increase in the input variable increases the output variable by one standard deviation as well. The mapped value regression coefficients, which are labeled as mapped values, indicate the degree to which a change of $+1\sigma$ for an input variable has on the actual values of the output variable [153].

Ground Risk Model

As mentioned in the section on the Literature Review, several studies have been conducted that attempted to predict the risk associated with UAS or manned aircraft operations. While they differed in their approach with respect to the source of the data to support predictions, all of the studies followed the same basic concept that is encompassed in the equation below, which appeared previously. This equation accounts for initiating events, exposure to risk, and the effects on bystanders.

$$E_c = \lambda_{System} * \rho_{Population} * P(Fatality|Impact) * A_{Impact} * SF$$

Equation 4

The four specific elements in this equation are:

1. How many people are in that area that could be affected ($\rho_{Population}$)?
2. What protection does shelter offer the people inside (SF)?
3. How large is the area affected by the air vehicle impact (A_{impact})?
4. Of the people affected, how many people are fatalities (P(Fatality|Impact))?

Population

First, the population density term will be addressed. All previous studies used a uniform population density value. While this is simpler to determine, it does not accurately reflect the way in which people actually spend their lives. This is important when considered in conjunction with the next parameter, which is shelter. Assuming that people are distributed uniformly throughout an area does not account for the amount of time people spend under shelter compared to in the open. To determine a more accurate reflection of population density, categorized by whether people are in the open, in their homes, in a car, or in some type of commercial building, additional research was conducted.

A two year study conducted from 1992 to 1994 on behalf of the U.S. Environmental Protection Agency tracked the behavior of people in a variety of settings on a daily basis. The purpose at the time of the study was to determine people's exposure to outdoor pollutants. However, the National Human Activity Pattern Survey or NHAPS resulted in a tremendous amount of data on how people spend their days in the United States. While the study was rich in information that covered human activity down to an hourly basis, a summary of the most pertinent data to this effort appears below in Table 9.

Table 9: Population Behavior Pattern Data

Information	Value	Units	Source	Citation
Time Spent in Residence	68.7	%	National Human Activity Pattern Survey	[148]
Time Spent Outdoors	7.6			
Time Spent in Vehicle	5.5			
Time Spent in Office/Factory	5.4			
Time Spent Indoors (Other)	12.8			

To determine the population density in each category Equation 5 was developed. The local population density refers to the actual density in the open, or in vehicles, etc. If one uses open areas as an example, the local population density is based on the overall population density of the area in question times the percentage of time people spend in the open divided by the percentage of land comprised of open space.

$$PopDensity_{local} = PopDensity_{overall} * \frac{Time\ Spent\ Ratio}{Area\ Coverage\ Ratio}$$

Equation 5

A graphical way to depict the difference between assuming a purely uniform population density and using behavioral patterns appears below in Figure 27. The diagram on the left depicts people as red circles uniformly distributed throughout the area in question. On the right, the same number of people is clustered into buildings, depicting their behavior with fewer people distributed in the open. A quick glance at the diagram on the right shows that there is more space unoccupied by people that could potentially lead to fewer casualties in a UAS crash sequence.

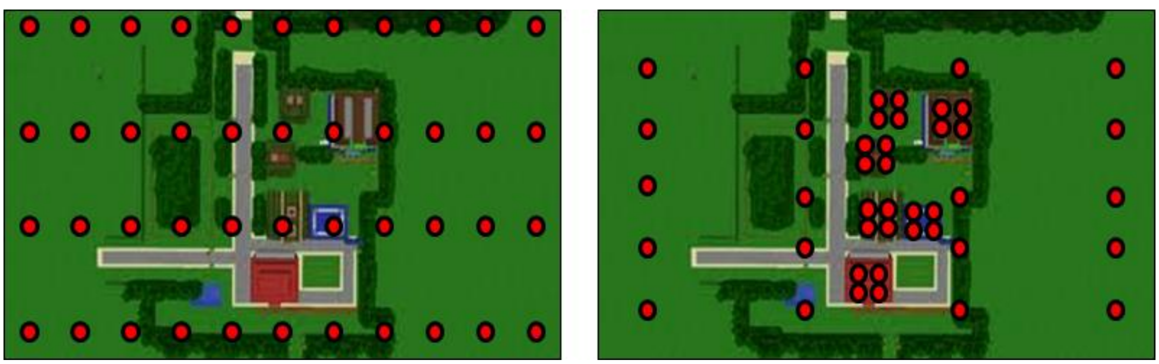


Figure 27: Population Density Patterns (Background Image [157])

To demonstrate the impact this method has on the local or specific population density for each shelter category, an example is offered. In terms of coverage, open space is by far the largest portion of land mass in the United States. However, people only spend on average 7.6% of their time outdoors, according to the NHAPS study. Thus the population density outdoors, or in an unsheltered condition, must be significantly lower than the average population density of an area. Figure 28 shows a typical breakdown for a given area into major categories. Figure 29 shows the breakdown in time spent in each major category, based on the NHAPS study. Given a nominal overall population density of 500 people per square mile, the localized population breakdown for each category appears in Figure 30.

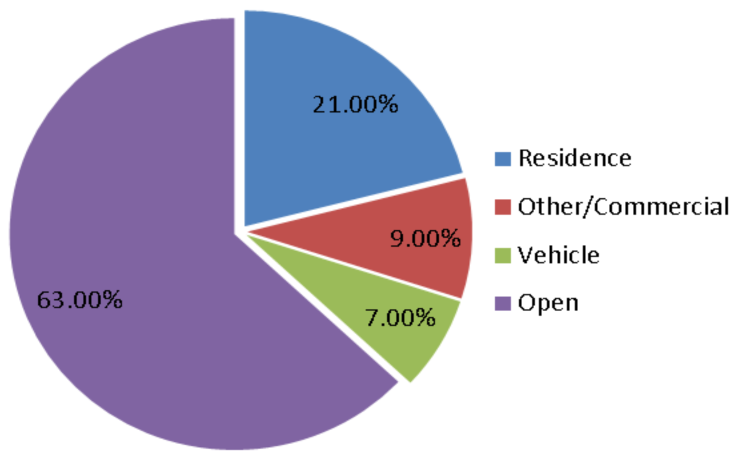


Figure 28: Percentage of Land Area Covered by Each Category

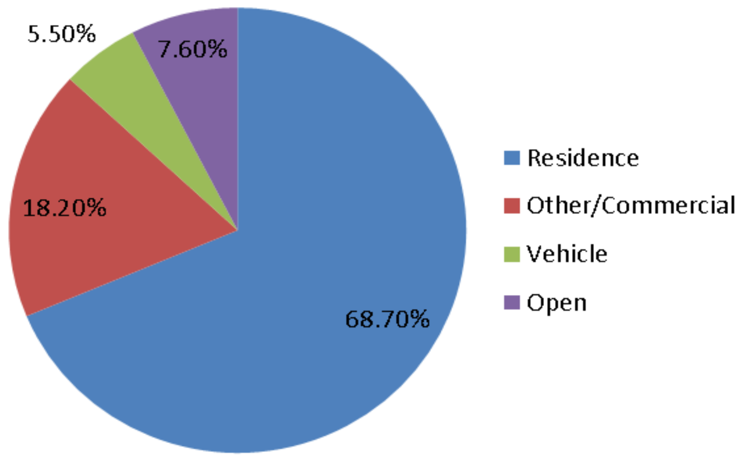


Figure 29: Percentage of Time Spent in Each Category

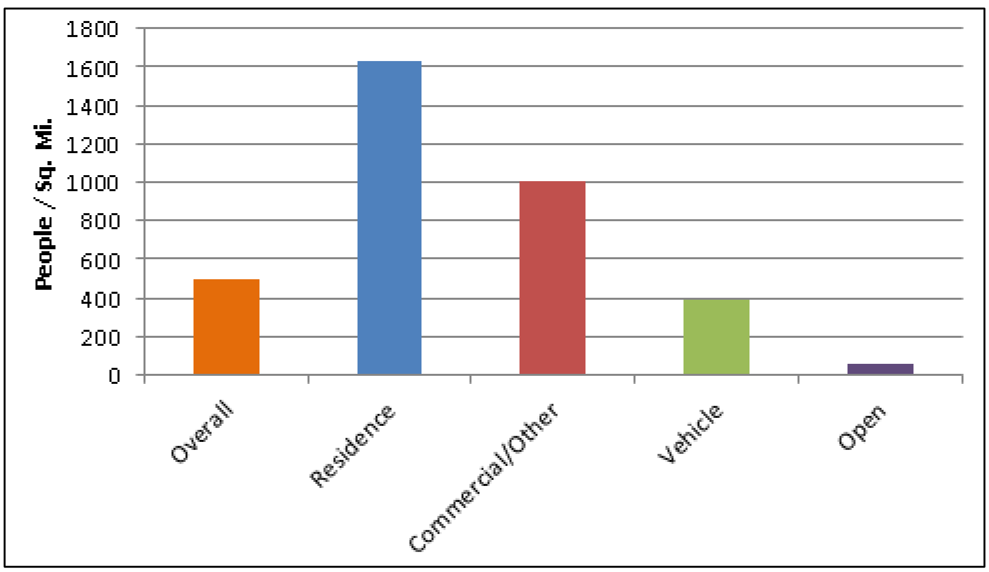


Figure 30: Local Population Density Breakdown by Category

What is evident from the results of this example is that the local population density in residential type structures is over three times the average or overall density. On the other hand, in open areas it is much lower than the overall, more than ten times lower. This has enormous implications for shelter factors, particularly in urban areas and with smaller UAS. Again, taking a realistic population distribution into account is only important if shelter is considered.

To demonstrate this, a hypothetical collision was estimated using the overall population density above of 500 people per square mile. The impact area of the crash was assumed to be 1000 ft^2. Three values for the number of expected casualties from this one impact were generated. The first value assumed a uniform population distribution. The second value allocated the impact area into portions based on the percentage of land coverage for each category from Figure 28. The third value used the same approach as method two, but added a shelter factor that made it 90% likely that people in a residence would be fatalities and 50% likely that people in a commercial building would be casualties. These values are theoretical at this point, and are simply to illustrate a point.

The results of the experiment appear in Figure 31. When the uniform population distribution and no shelter is considered, the casualty rate is highest, as expected. Continuing with a uniform population distribution and using shelter factors, the casualty rates decrease slightly by about 6.6%. However, when a logical approach to shelter factors is provided to the distributed case, the casualties are reduced by 37.7%, compared to the original case. That is because a larger percentage of people are under some form of shelter. This fact plays an important role in predicting casualties in the ground risk model because to ignore the actual behavior patterns of people would cause casualty predictions to be too high, therefore restricting UAS operations unnecessarily.

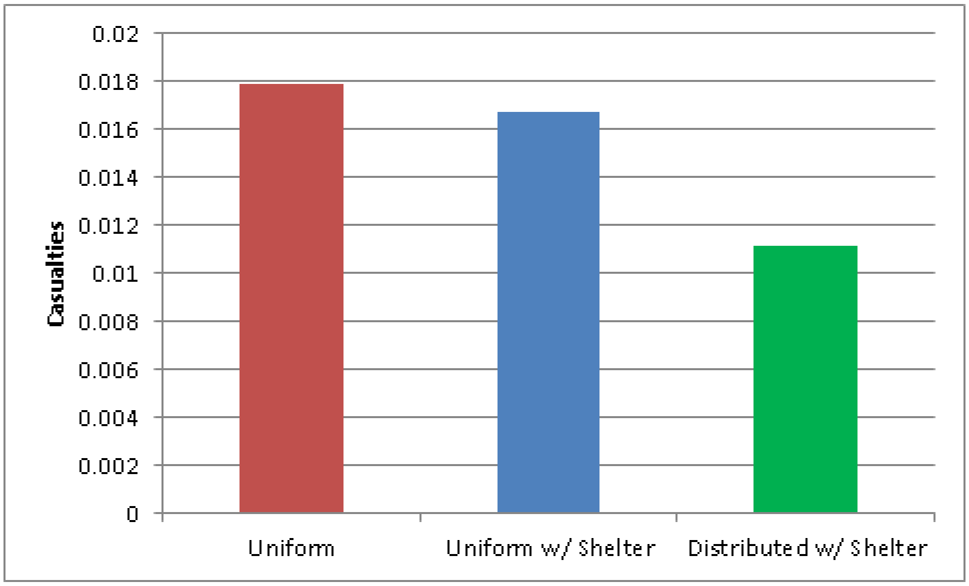


Figure 31: Population Distribution Sample Casualty Comparison

Shelter Effects

If an air vehicle does strike a building, vehicle or anything that could provide protection, it is imperative to determine what level of protection that shelter provides. A key shortcoming of several previous ground risk studies was the lack of shelter inherent in the model, or broad assumptions about the probability that vehicles would penetrate and cause casualties in a building. While the exact composition and materials used in buildings throughout the country is a very complex situation that cannot be assessed in complete detail in a study of this manner, data does exist that can better define shelter factors. For example, there is a very comprehensive study conducted by the Columbia Accident Investigation Board (CAIB), conducted in the wake of the Columbia tragedy that attempted to quantitatively assess the risk to people on the ground based on debris falling from another shuttle reentry.

The study used extensive GIS data for a large swath of land in the Texas and Louisiana area to determine ground usage, building types, roof construction and population patterns. Based on this information, the author was able to group building types into one of two broad categories: Residential or Commercial, and assign a shelter value to each one. The Residential structures, comprising roughly 20% of all buildings have roofs made of wood or similar materials. Commercial buildings, on the other hand are made of concrete or steel. The material choice was critical to determine the ability to shelter occupants from an air vehicle crash.

A summary of the types of materials found in most buildings in the representative sample from the Columbia study can be found in Table 10. The majority of structures were wooden, with steel or light metal, and concrete making up the next two categories. The remainder was tile or other categories that would have the same properties of wood typically. These values were used to help determine the shelter breakdown in the ground risk model.

Table 10: Roof Material Breakdown

Information	Value	Units	Source	Citation
Wood	58.4	%	NASA Columbia Report	[108]
Steel / Light Metal	4.9			
Concrete	9.2			

If an air vehicle does strike a building, the next determination is whether the vehicle can penetrate the building. In other words, does the building provide adequate shelter? Clothier, et. al. [158] incorporated some level of protection in their analysis for an article on UAS certification categories. The article discusses the use of corrugated iron and reinforced concrete as two potential roof structures. However, the Clothier article does not expound on the probability of encountering these types of roofs in the various environments UAS may operate over. The article also assumes that everyone inside a building is a fatality in the event of a building penetration. This assumption is analyzed in more detail in this effort using studies on earthquake and explosives damage to buildings.

To help determine whether a fallen air vehicle can harm people inside a structure, another study on shelter was used to determine the amount of energy different roof types could absorb. The study was conducted by the Department of Defense to determine the amount of shelter required to protect people from explosives. The amount of energy the various roofs could absorb appears below in Table 11.

. To simplify calculations, the model characterized residential buildings as being made of materials between panelized wood and lightweight concrete (600-2000 ft-lbf absorption). This range takes into account both urban and suburban wooden residential structures as well as more urban high-rise and apartment-style residential buildings. Commercial buildings were modeled as 4” Reinforced Concrete (RC). These values were seen as reasonable representations of the broad class of building materials used while also being conservative in nature. Vehicles were characterized as automobile steel for their absorption values.

Table 11: Roof Material Absorption Data

Information	Value	Units	Source	Citation
14" Reinforced Concrete	200,000	Ft-lbf	DoD Explosives Study	[151]
4" Reinforced Concrete	10,000			
2" Lightweight Concrete	2,000			
Medium Steel (18 gauge)	1,000			
Wood Panelized	600			
Light Metal (22 gauge)	500			
Plywood and Wood Joist	300			
Gypsum / Fiberboard / Steel Joist	200			
Steel (Automobile)	200			

To determine whether the air vehicle actually penetrates a structure or not, one needs to know the energy the vehicle possesses on impact. The amount of kinetic energy was based simply on the mass of the air vehicle and a value of 1.4 times the maximum speed of the vehicle. The 1.4 value was proposed by Dalamagkidis in a paper on ground risk for UAS [95]. While it is certainly likely that a falling air vehicle could encounter the ground with less velocity than this, the value was chosen as a way to conservatively estimate the terminal velocity of a falling air vehicle without having to calculate the actual drag on the vehicle.

To illustrate the effect that using kinetic energy and shelter values based on material properties has on the analysis, an example is used. A four pound vehicle traveling at 60 knots would have approximately 640 ft-lbf of kinetic energy on impact. Assuming that all of that energy is transferred to the structure in question means that this relatively small vehicle would penetrate all of the roof materials in Table 11 up to and including wooden roofs. Based on the information from Table 10, wooden roofs account for almost 60% of the structures in the country. However, the Weibel report assumes that a nine pound air vehicle, having over twice the mass as the example, would only penetrate 10% of structures [91]. Clearly this is a discrepancy. Without any corroborating data to support the estimates proposed by other studies, the results based on DoD and NASA analysis were used.

However, the author felt that the kinetic energy of the air vehicle was not sufficient to estimate the damage the vehicle could cause on the ground. An article that analyzed the impact to the World Trade Center buildings in September, 2001 describes the tremendous amount of damage caused by the fire from the fuel onboard the two airliners. The study demonstrated how the amount of chemical energy in the fuel load of an aircraft is significantly higher than the kinetic energy of the vehicle. The study shows that the fuel used in aircraft has a chemical energy value of 14,434,673.7 ft-lbf per lbf of fuel [150]. Therefore, the energy contained in each vehicle in this thesis was a combination of kinetic and chemical energy, in certain circumstances.

Chemical energy was analyzed in some crash circumstances, because not all aircraft crashes result in fire. In fact, a study conducted to determine occupant safety in General Aviation crashes determined that only 13% of such incidents resulted in an aircraft fire [159]. As a result, the model incorporates that logic and only includes chemical energy in the penetration decision in 13% of all crashes. It was felt that the assumption to equate the unmanned air vehicles with GA statistics was valid because UAS most closely resemble their GA counterparts in terms of structure and safety mechanisms.

The other aspect of any shelter considerations was to determine what the air vehicle would impact during a crash sequence, depending on what type of population area the vehicle was flying over. If someone wanted to determine the physical decomposition of a specific geographic area to study, this step could be conducted with sophisticated imagery and Geographic Information Systems (GIS). However, the purpose of the research in this thesis was to analyze statistical safety so a way of estimating ground coverage areas for the ground in more general terms had to be determined.

An article on using high resolution imagery to determine building ratio, or the ratio of the ground in a given area covered by buildings used statistics typically used to estimate radio wave propagation to propose typical estimates. Those values appear below in Table 12 and can be used to determine estimates of the probability of hitting a building or an otherwise open area, based on the location of the air vehicle crash. The author linked these building density values to the population density definitions of Suburban, Residential and City Center areas so that building density ratios were actually a function of population density.

Table 12: Building Density Estimates

Information	Value	Units	Source	Citation
Suburban	<20	% of Land Covered by Buildings	IEEE Article on Satellite Imagery	[160]
Residential	20-50			
City Center	50			

Impact Area

Perhaps one of the most critical, yet widely varying parameter in the ground risk model is the exposure area to risk caused by a UAS impacting the ground. This parameter is important because, when used in conjunction with the population density parameter previously discussed, it determines the number of people exposed to risk on the ground in the event of an air vehicle impact.

While there are several different methods that have been proposed to estimate the impact area, they fall into a few distinct, categories. The first distinction is between hypothetical and empirical prediction methods. In the former, several studies have tried to predict what the impact area of a UAS would be, typically based on the physical dimensions of the UAS and geometry of the descent. In the second category, several studies have used information from aircraft crashes in an attempt to determine a way to predict the impact area. These methods can be further broken down into weight-based, size-based, and aircraft category-based prediction techniques. A summary of the major techniques used appears below.

Table 13: Comparison of Impact Predictions

Information	Equation	Source	Citation
Hypothetical, Physical Dimensions and Geometry Based			
Planform Area	N/A	Weibel ICAT Report	[91]
Gliding Area	$(W_{span} + 2 * R_p)*(L+D_{glide} +2 * R_p)$ $D_{glide} = H_p / \tan(\gamma)$	Clothier Paper and Lum Paper	[88, 161]
Steep Area	$\pi * (0.5 * W_{span} * R_p)^2$		[92]
Skid Area	0.06 Mile Skid for GA Aircraft 0.3 Miles for Air Carrier	Solomon Paper	[162]
Combination of Skid and Overflight	Based on Wingpspans and Mean Skid Distances	DoE Standard	[163]
Empirical, Weight-Based			
Debris Area in Built Up Areas	1.0764 ft^2/lb MTOW	Ale and Piers	[96]
Debris Area in Open Areas	1.3455 ft^2/lb MTOW		
Impact Area	0.25 Hectares per 100 Tons MTOW	Eddowes Study	[89]
Debris Area	Log(Area) = -8.53 + 0.80 * Loge (MTOW) Area (Hectares, MTOW (kg)	NATS Study	
Empirical, Size / Category -Based			
Small Aircraft Steep Impact	1.3 Hectares	RAND Study	[164]
Large Aircraft Steep Impact	3.89 – 5.18 Hectares		
Small Aircraft Shallow Impact	2.59-3.89 Hectares		
Large Aircraft Shallow Impact	5.18 – 6.48 Hectares		
Other Aircraft	0.12-0.92 Hectares (Depending on Type of Fire Effects)	ACARRE Study	[89]
Scheduled Aircraft	0.95-19.95 Hectares (Depending on Type of Fire Effects)		

R_p = Radius of Person
H_p = Height of Person
L = Acft Length
γ = Glide Angle

Typical values for the dimensions geometry-based assumptions tend to be:

Table 14: Gliding Impact Area Input Values

Information	Value	Units	Source	Citation
Radius of Person (R_p)	0.8	Ft	Waggoner	[90]
Height of Person (H_p)	5.74			
Glide Angle (γ)	1.9-3.2	Degrees		

Since the impact area parameter is so important to the ground risk model, the next section of this effort will examine which method promises to yield the most accurate results. Some of the hypothetical prediction methods do not appear to make sense simply based on the logic used to develop the method. For example, it does not seem reasonable that an air vehicle would essentially settle vertically to the ground in a crash sequence and only affect an area as large as the physical dimensions of the planform area of the vehicle. The gliding assumption for impact area is slightly more credible, especially when considering the fact that a Defense Science Board report indicates that, in contrast to manned aircraft, over one-third of all Class A UAS accidents were caused by propulsion failures [165]. However, this method also assumes that potential casualties are all exposed in the open and that nothing acts to impede the forward glide of the UAS as it nears the ground. Again, this scenario is not likely but will also be analyzed in the context of developing the casualty prediction model.

In order to explain some of the methods above, further explanation is necessary. In the geometric methods, the dimensions of the air vehicle are used. The planform method is self-explanatory. In addition to that method, the author examined another method called the flat area method which simply uses the wingspan and length of the vehicle and assumes that the impact area is a rectangle based on those dimensions.

The gliding methods assume that the vehicle is gliding at some angle, typically based on assumptions about the lift to drag ratio of the air vehicle in descent. The impact area consists of a rectangle as wide as the wing span of the vehicle and as long as the descent from the top of a theoretical standing person's head to the point of impact. In the steep geometric assumption, a circular shape based on the vehicle wingspan is used which assumes a vertical descent. In addition, a hybrid model was explored that used an impact area value that was the average of the steep impact area and gliding impact area calculations. Skid area calculations are similar but also use empirical or hypothetical data to account for the aircraft skid after impact. Both the gliding and skid area methods assume that the vehicle does not strike anything that impedes forward progress.

In the empirical category, one study in particular, analyzed the impact areas of several aircraft in an attempt to quantify third party risk near an airport in the Netherlands. Using information from actual crash sites, the author developed a linear relationship between aircraft maximum takeoff weight and crash size [96]. A graph of the data used in this study appears in Figure 32.

It is important to note that this data was based on larger aircraft than would be expected of the air vehicles used as UAS. However, the fact that the impact areas are based on larger aircraft could actually tend to make the estimate more conservative when used for UAS but also take into account the reality that a crash could impact a larger physical area than simply the dimensions of the air vehicle itself. This chart takes into account the fact that the air vehicle can explode or at least fragment causing casualties over a larger area. The data used in the study also examined the impact area for both built up areas, wooded areas, and open areas.

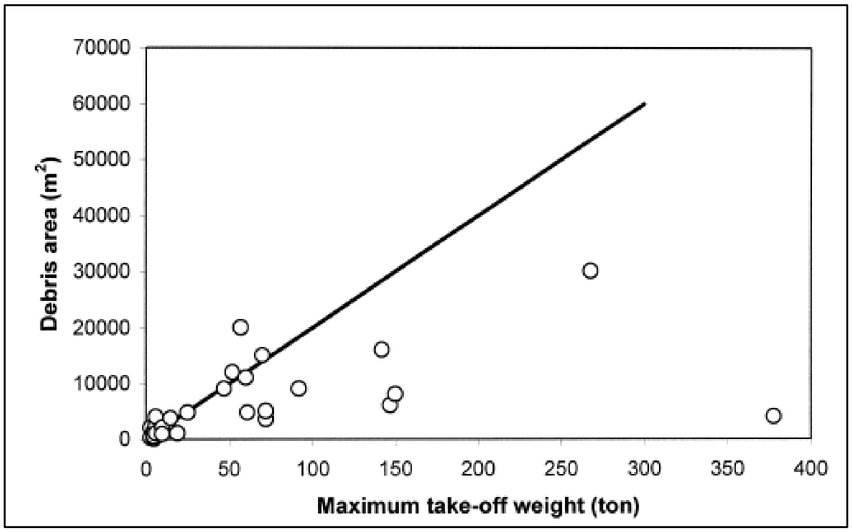


Figure 32: Estimate of Impact Area [96]

The values used to determine the impact area for a vehicle crash, based on maximum take-off weight appears in Table 15. The authors, Ale and Piers, focused on built up and open areas and ignored the impact area values for the wooded areas in the study for two reasons. One, the wooded estimate was the lowest value of the three so to be more conservative, this value was neglected.

Table 15: Impact Area Calculations

Information	Value	Units	Source	Citation
Debris Area in Built Up Areas	1.0764	ft^2/lb MTOW	Ale and Piers	[96]
Debris Area in Open Areas	1.3455			

Similar studies by Eddowes and NATS also used crash data from relatively few data points to compare the weight of the vehicle to an impact area estimate. The Eddowes study analyzed approximately 30 crashes near Manchester and the NATS study used 126 crashes tried to determine if a non-linear relationship was a better fit than a linear one [89]. The RAND study on third party risk around airports by Brady and Hillestad used a combination of historical data and some hypothetical estimates on skid distance and the impact area used by the Department of Energy for aircraft crash risk estimation around nuclear facilities [164].

While no database of crash impact areas from manned aircraft was available to compare the various prediction methods to actual crash data, it was possible to examine select aircraft crash reports to determine if the values will predict accurate results. For this purpose, several NTSB crash reports were examined. The reports were selected because they represented a range of aircraft sizes and because there was sufficient information in the reports to calculate the impact areas. To determine the actual impact area, the description of the wreckage information in the NTSB reports was examined. In some cases the wreckage information was more explicit and in other cases it had to be determined based on a description of the length of the impact and the width of either the wingspan or fuselage.

Several of the crashes are of note. One was a GA crash from 1979 in Ohio which was significant at the time because the pilot at the controls was a New York Yankees player, Thurman Munson. The aircraft was a Cessna Citation 501 and the crash occurred during an attempted landing in which the aircraft stalled. Based on the description of the first ground strike and subsequent skid, the aircraft covered approximately 290 feet in the skid [166]. With a known wingspan of 47 feet, this impact area would encompass approximately 13,630 ft^2.

Another example is a Korean Air flight 747 that crashed in Guam in 1997. The incident was a controlled flight into terrain, unlike the Cessna incident which involved a stall and loss of control. The NTSB report described the wreckage area as approximately 2,100 ft long and 400 ft wide for an impact area of 840,000 ft^2 [167]. A third example is a Learjet 35 that crashed into open terrain. The report describes the impact area as roughly 500 ft long by 48 ft wide for a total of 24,000 ft^2 [168]. A fourth accident report, involving a 727 that crashed while attempting to land details an impact area 2,064 ft long that varied in width from 29 to 120 ft. Based on these values, the impact area could range from as low as 59,856 ft^2 to as high as 247,860 ft^2 for an average value of 153,768 ft^2 [169]. Another interesting data point was a crash test conducted on a DC-7 aircraft in 1965 [170]. A report on the test details the impact and aftermath of a controlled crash. The reports for all of the crashes were obtained from the NTSB and include a Cessna 310 [171], Cessna 501 [166], CASA 212 [172], Learjet 35 [168], DC-7 [170], 727 [169] and 747 [167].

The next three figures demonstrate the results of comparing the actual or approximated impact area based on accident reports, with the predicted impact areas using the various prediction methods. To calculate some of the predictions, publicly available information on values such as takeoff weight, planform area, or wingspan was used. Figure 33 shows the percent deviation from the actual impact area for each of the prediction methods. The values generated from the RAND study techniques were removed because they predicted impact areas so large that their inclusion in the figure made it difficult to interpret the rest of the methods. It is important to note that the RAND study also used a factor of 0.3 to determine the number of casualties in the impact area. However, the impact areas predicted by the RAND values were typically ten times greater than the closest values from other methods so that the number of casualties would not equalize. All of the figures feature the aircraft in order from lightest to heaviest to see if there are any trends in the prediction methods with respect to aircraft size or weight.

Figure 34 shows the average value of the deviations from actual values. However, since some methods over and under-predicted results, the average could tend toward zero despite wide fluctuations. To prevent that problem, Figure 35 was developed which shows the average of the absolute value of the deviations. This last figure shows the overall degree to which a method tends to predict accurate results.

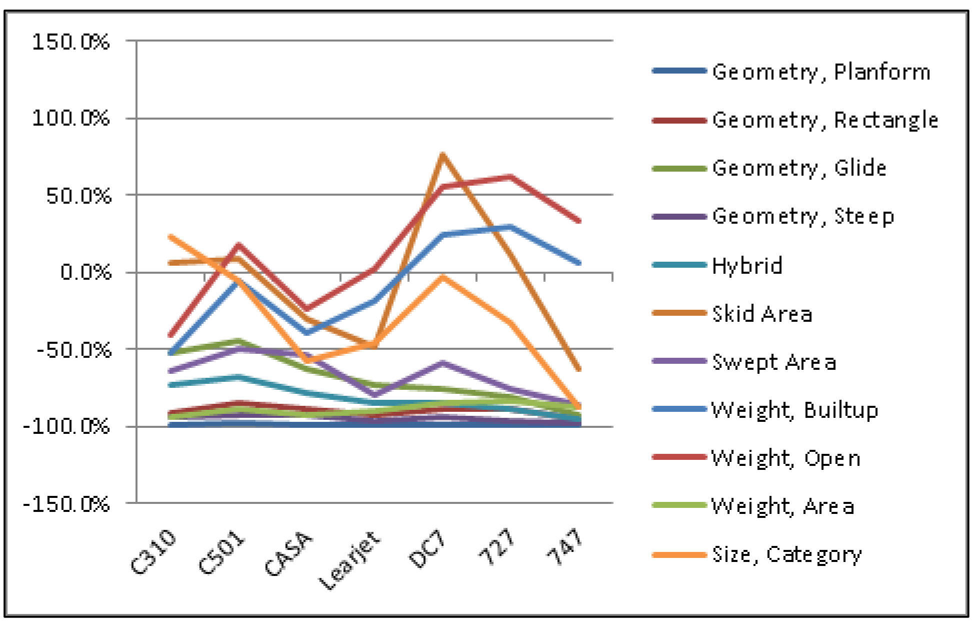


Figure 33: Deviations in Impact Area Predicted vs. Actual Impact Area

Based on these results, the two weight-based methods from Ale and Piers and the ACARRE (light orange) methods based on aircraft category (Scheduled / Other) follow roughly similar patterns. It is important to note that for the ACARRE calculations, the low value of each range was used to determine impact area, which ignored the fire area in that method. This is likely the cause of that method under-predicting the impact area of the larger aircraft. The skid area method from Solomon (dark orange) also followed the same general trend, but had a wider deviation for two of the data points.

All of the geometric methods consistently predicted smaller impact areas than the actual data. The geometric method that came closest to the result was the gliding approach. Initially, when the average of all results was taken in Figure 34, it appears that the skid area approach outlined by Solomon produces the best results. However, a review of Figure 33 indicates that the skid area approach deviations fluctuate quite a bit above and below the actual data.

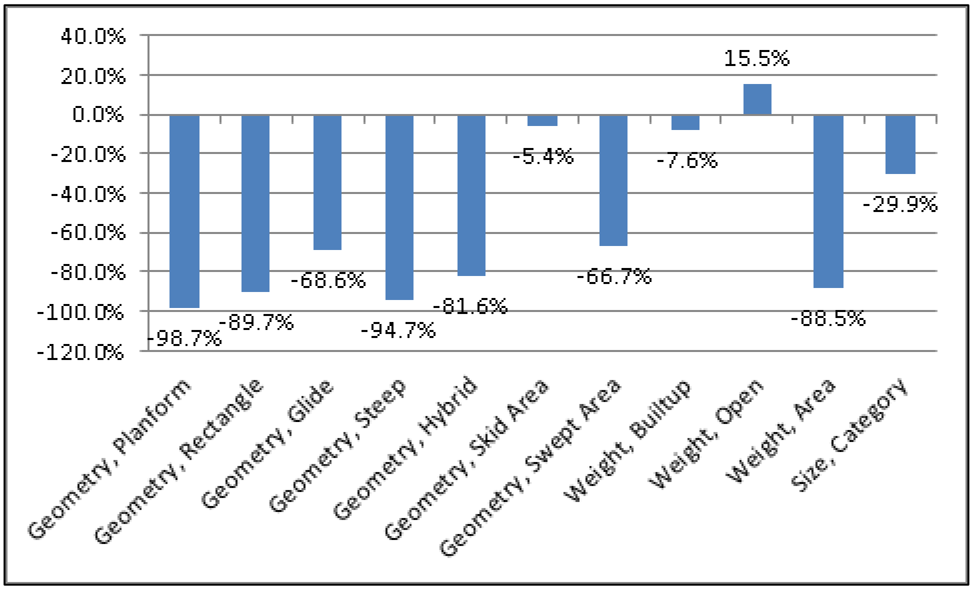


Figure 34: Impact Area Deviations (Average Values)

In fact, when the averages of the absolute values of the deviations are compared in Figure 35, the two weight-based methods from Ale and Piers produce the predictions closest to the actual data. When the data from the accidents listed above is analyzed for a linear fit, the impact area does indicate a good linear fit based on vehicle weight. The results of the fit indicate a relationship of:

$$Area(ft^2) = -2475.466 + 1.001 * Weight(lbs)$$

Equation 6

The slope value is fairly similar to the value described by Ale and Piers in built up areas which is 1.0764 ft^2/lb. The regression data indicates a linear fit with an R^2 value of 0.997.

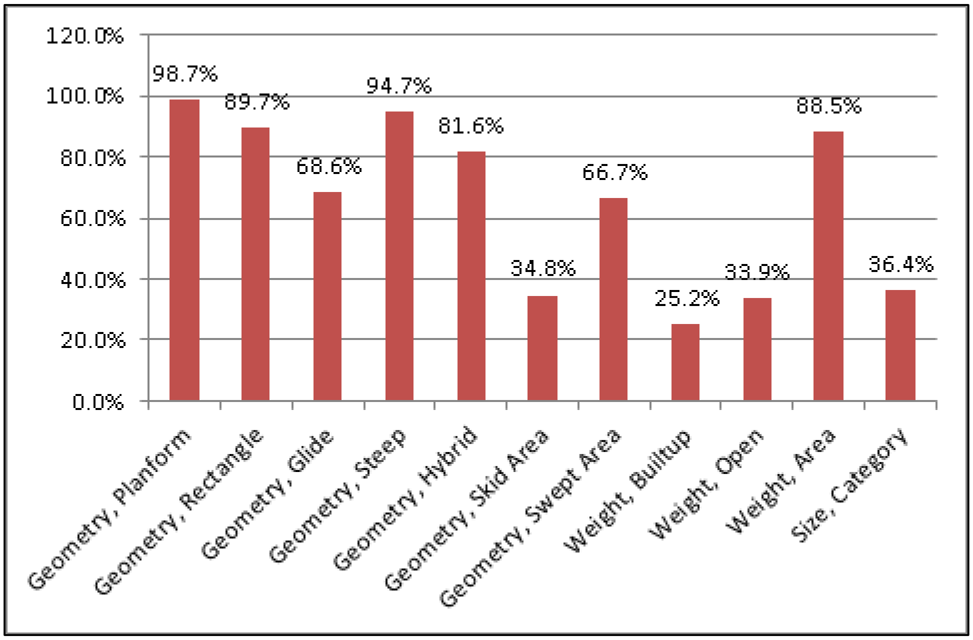


Figure 35: Impact Area Deviations (Average of Absolute Values)

These examples serve to bolster the empirical data used by Ale and Piers in their study and provide the best available prediction of impact area for use in this thesis. While the skid area prediction method from Solomon is also very close, it uses a discrete value for skid length that would not provide continuous results. Therefore, the author decided to use the Ale and Piers method due to the fact that it appears to provide the best predictive capability for impact area and is easy to implement in a model due to its linear relationship to vehicle weight.

It is important to note the results of a comparison conducted on the prediction methods using a smaller aircraft, based on a Cessna 172 airframe. Although, there was not a valid accident report to develop an estimate of an actual impact area, the various prediction methods were utilized to compare results, which appear in Figure 36. The results indicate that for a lighter aircraft, the gliding and skid area predictions are larger than all of the other prediction methods, including the weight-based methods. This is obviously important when analyzing UAS, which in the near-term, will tend to be lighter than most manned aircraft. What this experiment may show is that the gliding and skidding prediction methods will tend to over-predict the impact area for aircraft that are relatively light, yet retain high aspect ratios and thus wide wingspans due to the lower airspeeds and long endurance requirements for UAS. More research on the best way to predict impact areas for light air vehicles is certainly required and in fact, should not be difficult to do given the relatively low cost of impact testing small, light vehicles.

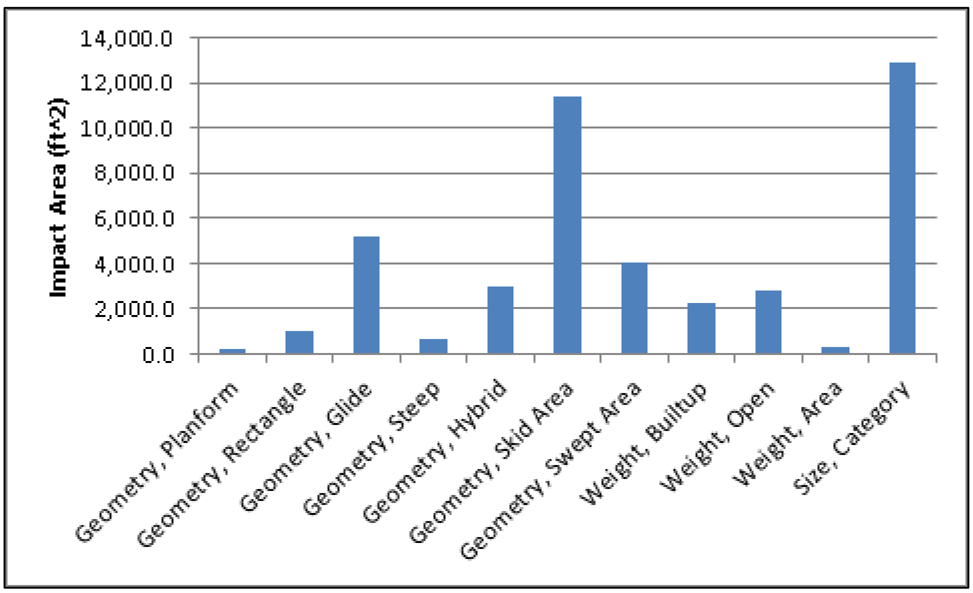


Figure 36: Impact Area Comparisons for C-172 Sized Aircraft

To illustrate the final point about the potential problem with several of the geometry-based approaches to impact area, an analysis of a theoretical air vehicle was conducted. The air vehicle was assumed to weigh 1 pound and be approximately 6 inches long with a 6 inch wingspan. When these values are used in the various impact area prediction techniques, the resulting values appear in Figure 37. Without any corroborating data, it is still fairly safe to say that the estimates for impact areas produced by the gliding, hybrid and skid methods are not sound. Because these techniques use an estimate for the length of the impact area predicated on an uninterrupted glide or skid, these techniques will produce large estimates even for extremely small vehicles. The hypothetical, gliding or skid-based methods under-predicted the impact areas for large aircraft, which would under-predict casualties for the most dangerous cases, and over-predicted impact areas for the smallest aircraft, resulting in overly conservative estimates for the vehicles that would suffer the most from unnecessary reliability restrictions imposed to meet safety requirements.

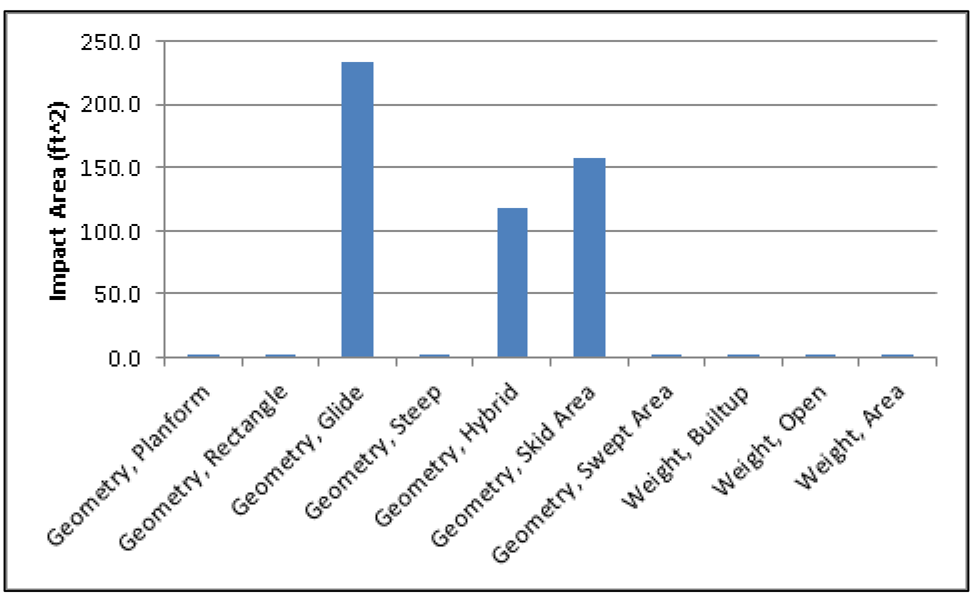


Figure 37: Impact Areas for Theoretical One Pound Air Vehicle

As an additional note, it is important to highlight that the values for impact area described in the Ale and Piers paper were calculated in 1992 for a study known as IMER. In 1998 another study was conducted on the safety around Schiphol airport in the Netherlands and different values to predict impact area were published. The values would predict a smaller impact area for a given maximum gross weight. However, the report also states that due to time limitations the analysis was not 'elaborate' [173]. In addition, the values do not match the regression done in this research from accident reports. As a result, until more compelling impact area analysis is published, the author used the original values from the NLR study.

Casualties

The next factor to consider is whether people in the impact area become casualties in the event of a UAS accident. The actual death or severe injury of a human caused by a falling object or debris is a highly complex problem. However, the study of injuries caused by explosives and debris is fairly extensive and can provide information helpful to this research. It is also important to discuss the difference between casualties in the open and those under shelter.

Casualties in the Open:

A Sandia report compiled for the Range Commander's Council developed data on the probability of fatality due to debris based on the area of the body impacted and the position of the body at the time of impact (standing, sitting, etc.). These values were based on extensive studies conducted in the 1960's using human cadavers and animals as well as gelatin models to determine the effects of fragments impacting the human body [107].

Both Figure 38 and Figure 39 show the more significant results of that report. The data bases the probability of causing a fatality on the kinetic energy of the particle that impacts the human body. In Figure 39 we can see that the median value of kinetic energy to cause fatalities is 58 ft-lbf. A similar study conducted for the U.S. Air Force's Space and Missile Test Center uses values of energy for fatalities between 35-50 ft-lbf [109].

A summary of all data obtained that related to fatalities caused by the kinetic energy of fragments or debris appears in Table 16. Overall, a value of approximately 50 ft-lbf appears to be an average kinetic energy value to cause a fatality. However, the kinetic energy of even a small air vehicle that weighs 4 lbs and travels at 60 knots is equivalent to almost 640 ft-lbf. This means that the kinetic energy in one small UAS at relatively low flight speeds has more than ten times the energy required to cause a fatality. As a result, the assumption in the model was that any air vehicle with more than 58 ft-lbf of energy that crashed was capable of killing everyone in the crash impact area, unless they were protected by shelter. This would be true for all but the smallest of air vehicles. The probability of causing a fatality for people protected by shelter will be discussed in more detail in the next sub-section.

Table 16: Fatality Data for Debris

Information	Value	Units	Source	Citation
Energy for 'Hazardous' Debris	33	ft-lbf	Air Force Development and Test Center	[109]
Energy for 'Hazardous Debris'	35-50			
Energy Required by Fragment for 90% Probability of Fatality	85		Sandia Report	[107]
Energy Required by Fragment to be Hazardous to Humans	58	Joules	DODD 6055.9	[110]
Probability of Fatality due to Debris	Log Normal Distribution: α: 44 β: 0.3737	Ft-lbf	Sandia Report	[107]

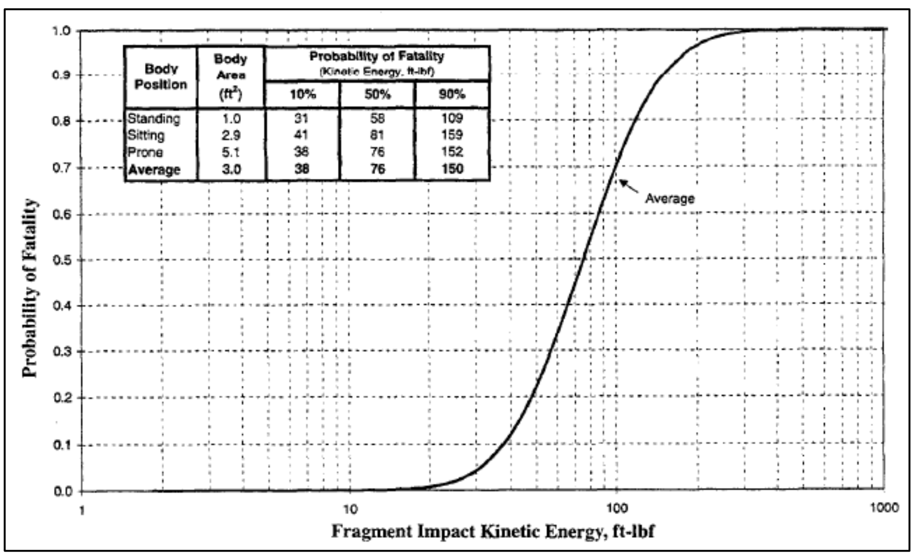


Figure 38: Probability of Fatality Based on Kinetic Energy [107]

Injury Level	Energy (ft-lbf)
Threshold	11
90% Injury (10% Fatal)	40
50% Injury (50% Fatal)	58
10% Injury (90% Fatal)	85

Figure 39: Energy and Fatality Summary [107]

Casualties Under Shelter:

The final piece of the ground casualty equation is whether people are killed by the UAS when it makes impact into a structure. The author needed to determine a way to estimate casualties if the structure was penetrated by the air vehicle. Once again, a physics-based approach that took into account the number of floors in a building, the internal construction materials and the energy dissipation of the total structure would be necessary to create a more thorough and detailed model. However, to analyze this problem at the statistical level required a more general approach.

As in previous cases, while no studies of UAS impact on buildings existed in the public domain, there were several general studies on the casualty estimation for building collapses or damage. The first one used data from earthquake events to estimate the expected percentage of casualties in a building due to a total building collapse, which is the worst case scenario. The next one was conducted by DoD to estimate the casualties in a structure damaged by explosives. The final four values offer mortality estimates in different types of buildings due to plane crashes. These values were published in a

RAND study conducted in conjunction with the risk assessment previously mentioned for the population around an airport in the Netherlands. The mortality estimates were based on previous studies conducted on nuclear facilities or other specific structures and estimated parametrically for the structures in question.

Table 17: Building Casualty Data Summary

<table>
<tr><th colspan="2">Information</th><th>Value</th><th>Units</th><th>Source</th><th>Citation</th></tr>
<tr><td colspan="2">Expected Deaths Due to Building Collapse</td><td>20-40</td><td rowspan="6">%</td><td>Earthquake Study</td><td>[117]</td></tr>
<tr><td colspan="2">Maximum Expected Deaths Due to Building Collapse</td><td>32</td><td>DoD Explosives Study</td><td>[151]</td></tr>
<tr><td rowspan="2">Mortality Rate for Medium Aircraft</td><td>Single-Family to few-Story Apartment</td><td>40</td><td rowspan="4">RAND Study</td><td rowspan="4">[164]</td></tr>
<tr><td>Office or High-Rise Apartment</td><td>30</td></tr>
<tr><td rowspan="2">Mortality Rate for Small Aircraft</td><td>Single-Family to few-Story Apartment</td><td>20</td></tr>
<tr><td>Office or High-Rise Apartment</td><td>10</td></tr>
</table>

What is both evident and noteworthy about these statistics is that the typical value for mortality rate under all of these different studies is approximately 30%. As a result, the author used this factor as a casualty rate for any building that was penetrated by an air vehicle. In other words, 30% of the people inside any building penetrated by a UAS were deemed as casualties. The remaining 70% are not affected. While the 30% value may seem low initially, it is important to keep in mind that this value is based on existing data that assumes a worst case scenario of a complete building collapse.

Summary

The primary aspects of the ground risk model that need to be addressed are listed below in the morphological matrix in Table 18. Combining various aspects from the morphological matrix can provide an overall modeling method for the ground risk that will be used as a basis for comparison in the validation efforts. The darker magenta combinations represent the simplest model available to estimate ground casualties. The lighter magenta boxes, when combined with any of the darker magenta boxes, represent a slightly more detailed ground risk model and the combination of modeling areas in green represent the terminal effects model described in this effort.

Table 18: Ground Model Morphological Matrix

Modeling Area	**Methods**		
Population Density	Uniformly Distributed		Based on Behavior Patterns
Shelter	No Shelter	Assumed Protective Value	Based on Existing Data for Roof Materials and Energy Calculations
Impact Area	Based on Aircraft Dimensions	Based on Gliding Geometry	Empirical Weight-Based Area
Casualties Inside Penetrated Buildings	N/A	All (Worst Case)	Based on Explosives and Earthquake Studies

Ground Risk Event Tree

The event tree for ground risk appears in Figure 40. The process begins on the left side with a ground failure rate term that can be modeled as a uniform distribution to represent a range of vehicles or as a deterministic value to represent a known vehicle. The next step is to determine the impact area that the vehicle affects if it crashes on the ground.

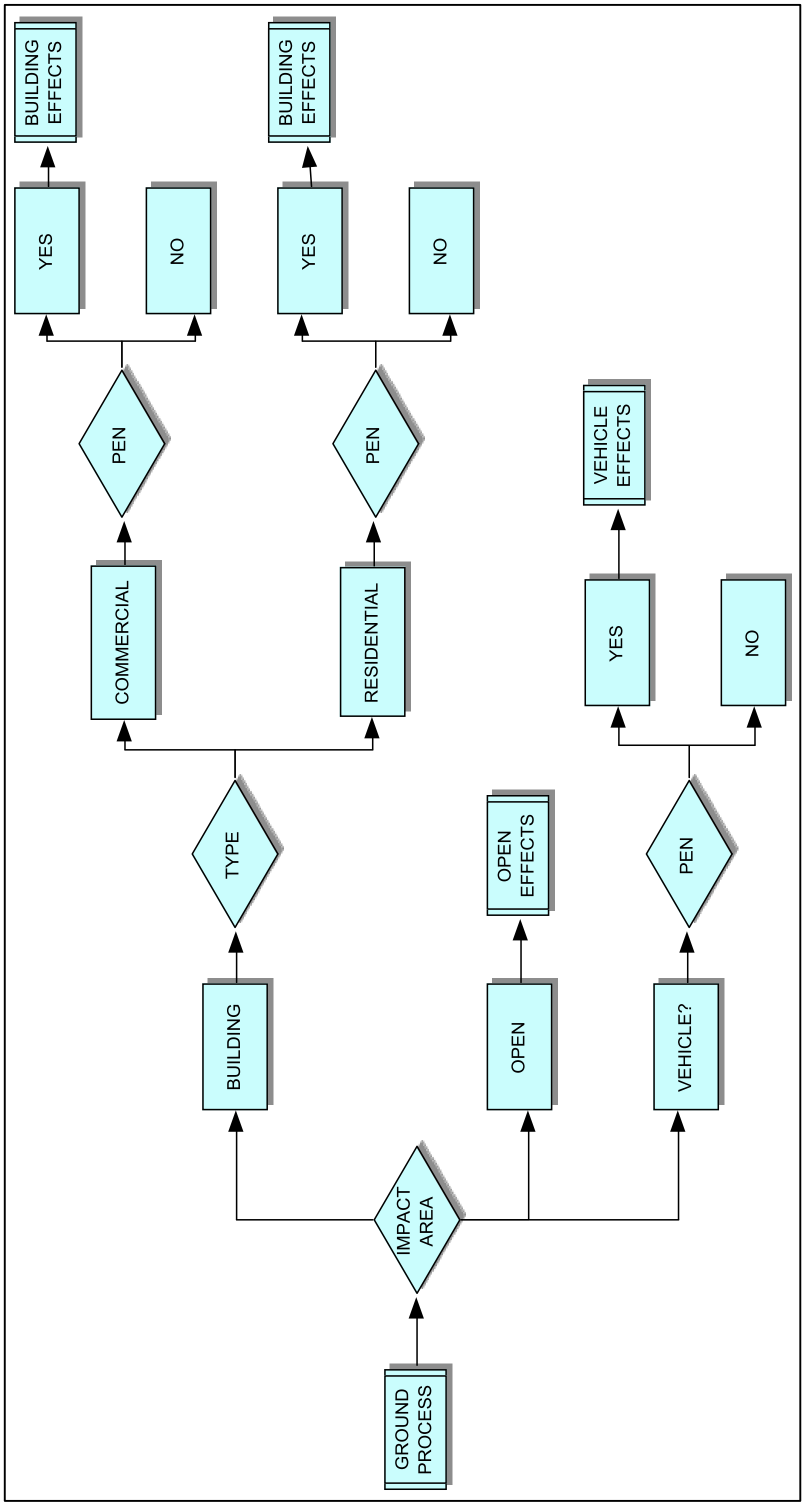


Figure 40: Event Tree for Ground Risk

As demonstrated in the sections above, the determination of expected ground casualties is a fairly complex logical process with several major inputs to develop one essential output: the casualty rate. In addition to the event tree, a graphic depiction of the inputs and their relationships is shown in Figure 41. This figure shows the primary information that serve as inputs into the ground risk model and then the data derived from those primary inputs. The final result is the expected casualty rate or the expected number of casualties per flight hour.

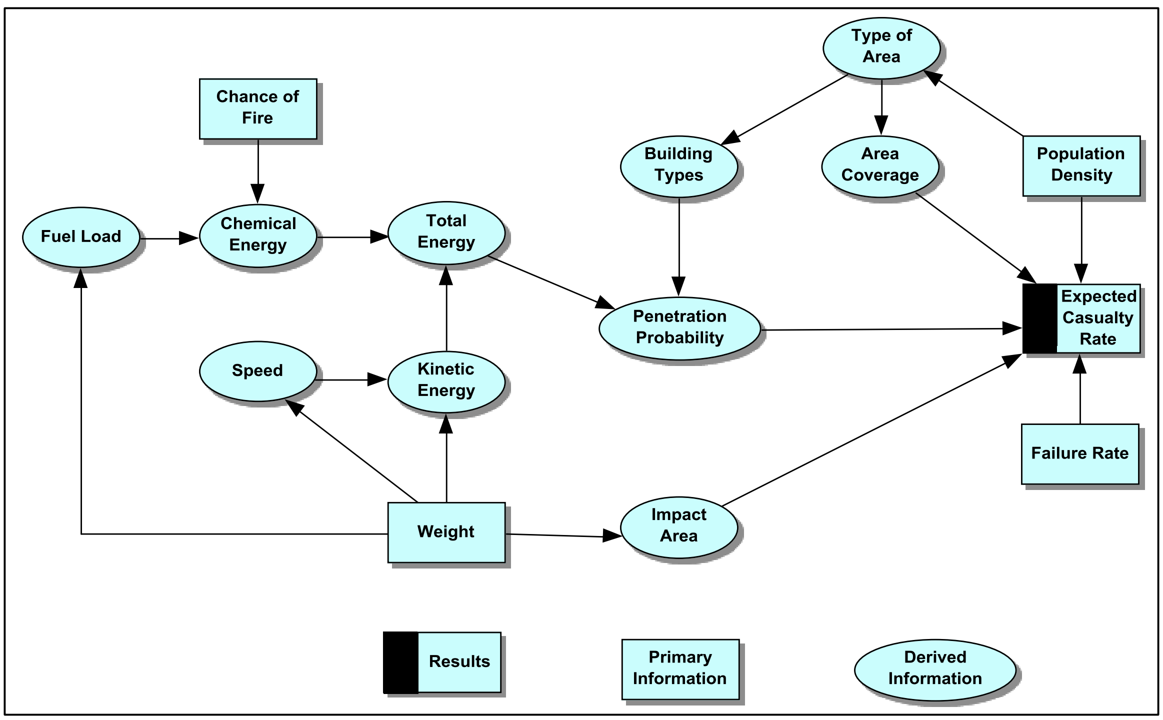


Figure 41: Ground Effects Relationships

In order to illustrate the actual simulation structure in the @Risk software suite, a screen shot of the event tree appears in Figure 42. While the values that appear in the spreadsheet at the time the screen shot was taken are not meaningful, the intent was to demonstrate how the Decision Tools suite offered an event tree format to the Excel spreadsheet to graphically depict the branches of the event tree in the same spreadsheet that the Monte Carlo simulation actually took place.

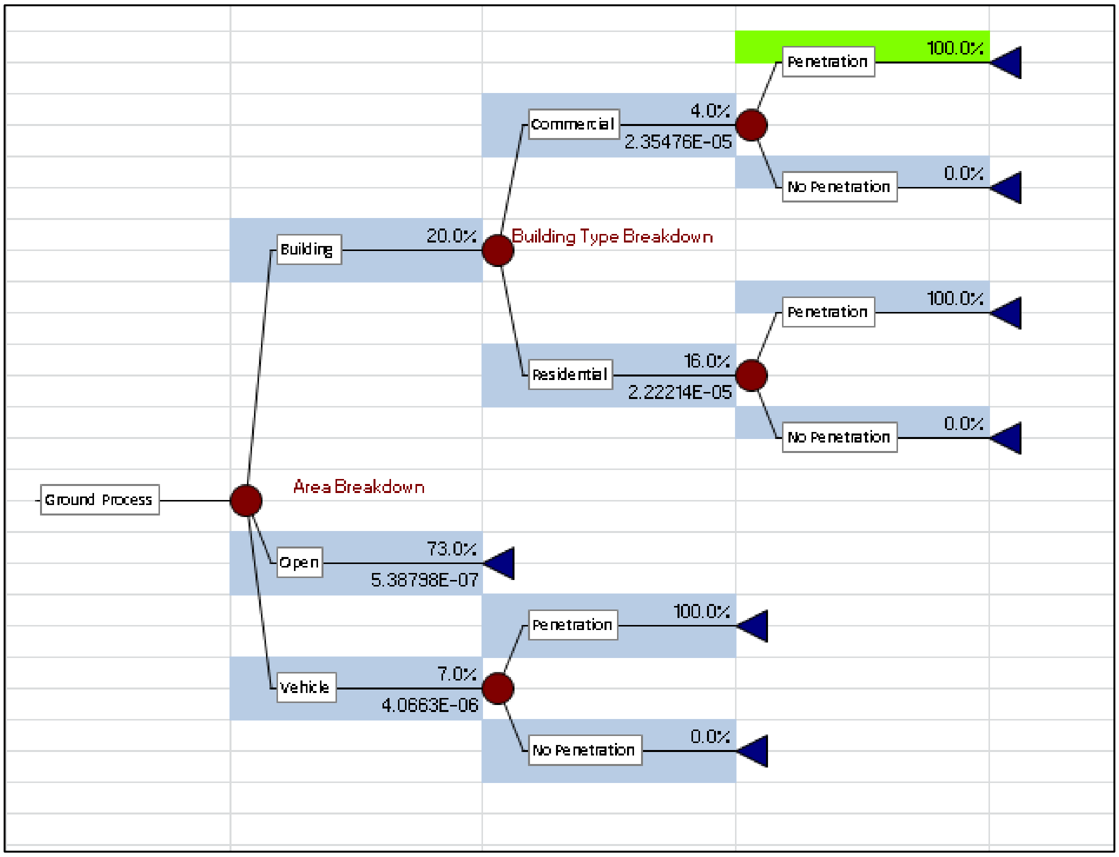


Figure 42: Event Tree @ Risk Format Example

A summary of the major assumptions that went into the ground risk event tree simulation appears below. While not the only assumptions made when building the model, these are the most critical and constitute much of the information necessary to bridge the gap between UAS failures and their risk of causing casualties.

- Crash debris area is based on UAS maximum weight

- Entire debris area is capable of causing a casualty, if the overall energy is high enough
- A building penetration is identical to a building collapse. Although a structure can provide shelter, if vehicle energy exceeds the material absorption properties of the roof, the penetration is viewed as total. In other words, there are no partial penetrations or collapses.
- 30% if building occupants will be fatalities in the event of a collapse
- No effort is made to avoid buildings in a crash sequence. Actual crash site is randomly distributed based on the percent coverage of structures or open space on the ground

In addition, an update of the ground model parameters comparing other studies with the methods advanced by this thesis appears in Table 19. The validity of these parameters will be explored in more detail in the Validation part of this section.

Table 19: Ground Risk Model Parameter Review

Model Parameter	Clothier	Evans *	Waggoner	Burke	Dalamagkidis	Weibel	Current Thesis
Population	Uniform	Uniform	Uniform	Uniform, Time-Weighted Average	Uniform	Uniform	Distributed
Shelter Effects	N/A	N/A	N/A	Linked to Population Density Variable	Incorporated into Casualty Calculation	Estimate Based on Vehicle Class	Energy-Based (Kinetic and Chemical)
Impact Area	Geometry-Based (Steep and Gliding)	Weight-Based (Non-linear)	Geometry-Based (Gliding)	Geometry-Based (Swept Area)	Geometry-Based	Geometry Based (Planform Area)	Weight-Based (Linear)
Casualties	All	30% in Impact Area	Left to User to Determine	All above 49 ft-lbs of KE	Based on Log Curve from RCC	All, if Penetration Occurred	All in Open Areas, 30% inside Shelter if Penetrated
Validated	No	No	No	No	No	No	Yes, Using GA and Air Carrier Historical Data

* Not originally intended for UAS

Ground Risk Model Validation

In order to validate the ground risk model, two cases were used. The first involved General Aviation statistics and the second considered Air Carrier aircraft. These two cases were chosen due to the availability of data and the fact that they represent aircraft across a range of sizes, weights, and safety levels.

Several times throughout the validation and subsequent sections of this paper, the terms simple model and full ground risk model will be used. These two methods describe ends of the spectrum on Table 18. The simple model is a ground risk prediction method that closely resembles the methods used by previous studies and captured by Equation 4. In this model, the population density is considered uniform, the impact area calculations are based on physical dimensions of the air vehicle such as the planform area or gliding area, and no protection from shelter is considered. The full ground risk model, on the other hand, consists of the event tree in Figure 40, and the effects shown in Figure 41 populated with all of the supporting data described in the section on the Ground Risk Model and summarized in the yellow column in Table 19.

General Aviation (GA) Validation

The first step in the process was to ensure that the ground risk model accurately represented the risk to bystanders on the ground due to a UAS crash. This was a particularly important step since many of the new approaches applied to this research pertained to the terminal effects of a UAS crash. In order to compare the accuracy of the model in this framework with other previous approaches, a parallel effort was conducted using methods previously found in the literature to predict UAS ground risk.

The ground calibration effort began by gathering historical data on UAS incidents and third-party fatalities caused by GA aircraft. Data for both the accident rate and fatality rate were available. It is important to note that the ground fatality rate in Table 20 only includes fatalities of bystanders and not the passengers or crew on board the aircraft. The dimensions for the aircraft were based on average values of the aircraft involved in accidents during the 20 year period in question.

One initial concern with the use of manned aircraft to validate a tool designed to predict UAS ground casualties was the fact that pilots on board have the ability to avoid buildings or other populated areas during a crash sequence and may have altered the ground casualty event sequence in some way. However, an examination of the causes of manned aircraft crashes reveals that this is only likely in a very small percentage of aircraft crashes. A report on Civil Aviation air accidents from 2007-2009 shows the various causes of fatal aircraft accidents, including problems such as weather, loss of control, propulsion failures and controlled flight into terrain. Engine and fuel related failures only accounted for 13.7% of all GA accidents and 18.9% of all Air Taxi accidents during the time period in question [174]. In the case of GA aircraft, the degree to which pilots could be expected to avoid built-up areas during an engine failure may also be limited due to the relatively low altitudes at which these aircraft tend to operate.

Table 20: General Aviation Data

Information	Value	Units	Source	Citation
General Aviation Accidents [1984-2004]	1.541	Fatal Accidents /100k FH	AOPA Website	[175]
Ground Fatalities Caused by General Aviation Accidents [1984-2004]	0.0084	Fatalities / 100k FH	NTSB Data from Clothier Paper	[176]
Weight	2100	lbs	Based on Average of Aircraft from NTSB Data	N/A
Wingspan	36	ft		
Length	29			

A key component of the ground risk model is the population density variable. This fact was reinforced during the sensitivity analysis discussed in the previous section. This value is important to the model because it determines how many people are potentially at risk in the event of a UAS accident. There are several different ways to determine the population density in the United States. In order to properly calibrate the ground risk model, several methods were chosen to compare how accurately they could predict ground casualties. The methods, which will be described in more detail below, were:

1. Average value
2. Worst-case
3. Accident-weighted
4. Continuous distribution based on state values

The average value method was the simplest and relied only on population statistics and the land mass of the United States. With these two values an average population density was calculated. The next method assumed that the majority of GA crashes occurred in the busier and more densely populated eastern Continental United States (CONUS). The average of the population density values for these states was used.

The accident-weighted method was slightly more complex. NTSB accident statistics also show which states the accidents occurred in. From that information it was possible to weight the population densities of the states in which more accidents occur more heavily in the overall density value. A graphical depiction of the accidents that occurred in each state appears in Figure 43. This figure was created by using the accident data listed above, broken down by state and inserted into a GIS software tool known as ArcGIS. The larger the bubble on the map, the greater number of GA accidents that occurred during the period in question.

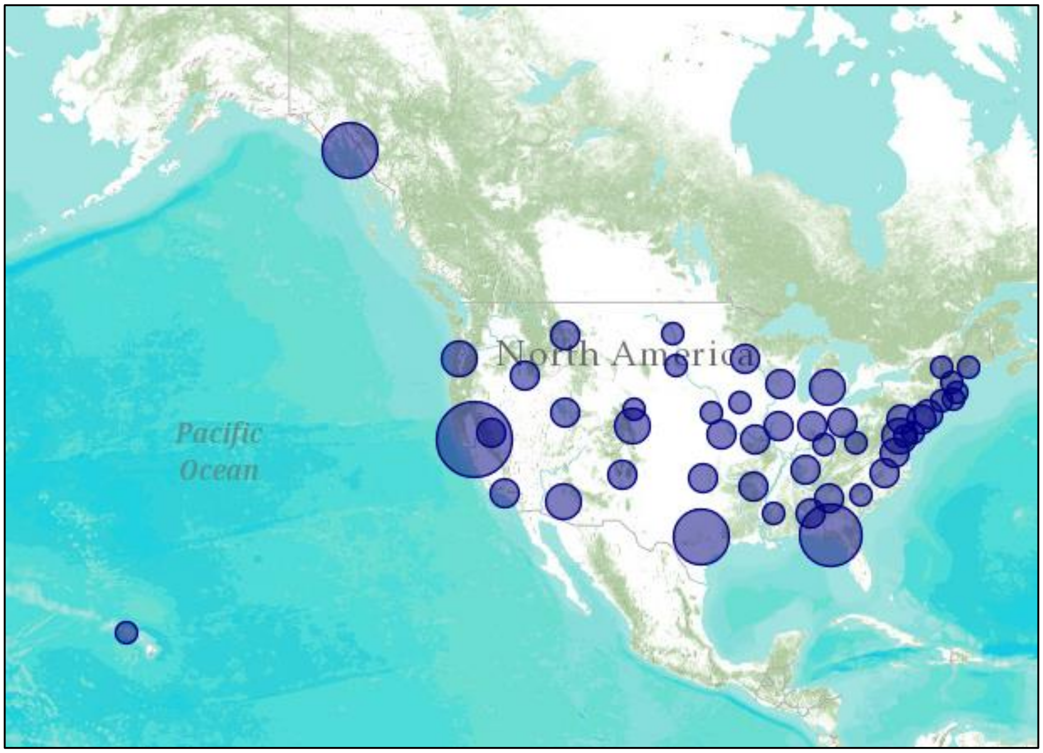


Figure 43: Locations of GA Accidents

Finally, in the last method, the population density of the United States was modeled as a probability distribution. First, a discrete distribution was created based on the land mass of each state and that state's corresponding density population. Next, the data was fitted and replaced by a truncated normal distribution. Using that normal distribution in the @Risk software tool, a simulation was conducted to replicate the different possibilities of population densities a GA crash would have likely impacted. A summary of the values used for all four methods appears in Table 21.

.

.

Table 21: Population Density Values

Information	Value	Units	Source	Citation
Average U.S. Population Density	79	People / mi^2	Census Data	[147]
Typical Eastern U.S. Population Density	1000		ArcGIS Data	[177]
Accident Weighted	170.94		NTSB and Census Data	[178, 179]
Population Distribution Derived from Discrete Distribution	*Truncated Normal:* Mean: 90.26 Std Deviation: 129.42 Min: 1.2 Max: 9856			

Once the four methods to determine population density were developed, the model was tested by running simulations with each of the four population density estimate methods and by using adding layers of complexity to the different aspects of the ground risk model as described in Table 18. While it is impossible to include the results of all of the different combinations of parameters, an example of the type of results obtained appears in Figure 44.

In this figure, the continuous distribution for population density was used in the GA validation effort and compared using three different impact area prediction techniques including a flat or rectangular impact area, a gliding area, and the weight-based method. In addition, the population was modeled as uniformly distributed for the three cases on the left and modeled using the previously discussed behavior patterns and with the protection of shelter for the three cases on the right. The vertical bars in Figure 44 represent the percent difference in the casualty rates predicted by the model and the historical casualty rates for the GA validation effort. The purpose of this process was to explore trends of the various model parameters.

For example, it is evident that using a uniform population density without consideration of shelter tends to over-predict casualties. In addition, the gliding method of predicting impact area also tends to predict higher casualties than the other two methods displayed in the Figure. The results of the model using the non-uniform population density method, and including all of the supporting data described in the section on the ground risk model match the historical results most closely.

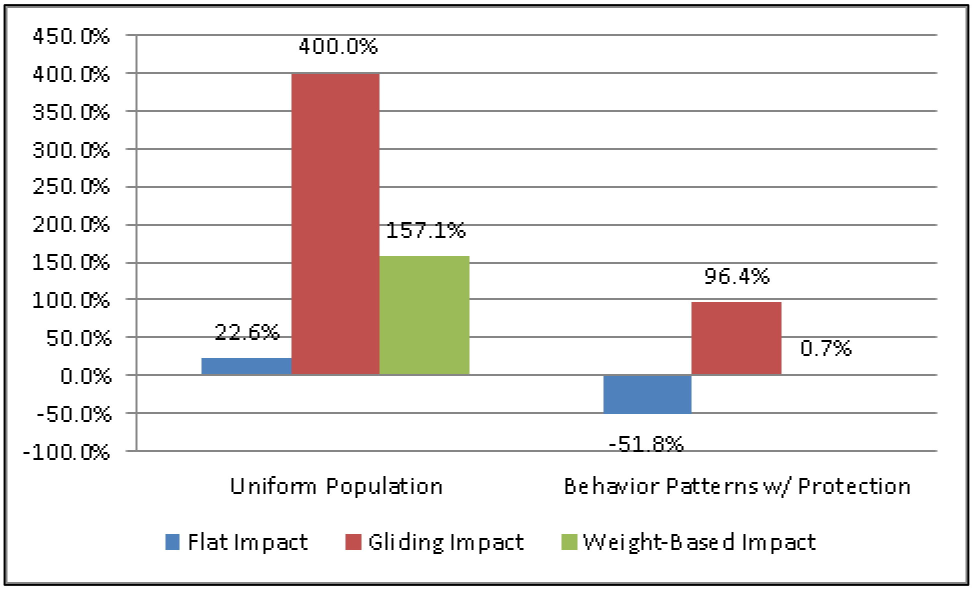


Figure 44 GA Validation Results Based on Impact Areas

To further explore the full ground risk model developed in this thesis, the model was used with the four techniques to model the nation's population density described previously. The results of the four experiments appear in Table 22 and Figure 45. Some of the trends apparent in this table are that the worst case method of modeling population density over-predicts casualties to a large degree. As seen above, the best match between historical data and the model's predictions occurs when the full ground risk model is utilized with the continuous distribution for population density.

Table 22: GA Ground Validation Results

Type of Population Estimate	Predicted to Actual Data:
Average	-39.8%
Worst Case	507.1%
Accident Weighted	29.8%
Population Distribution:	0.7%

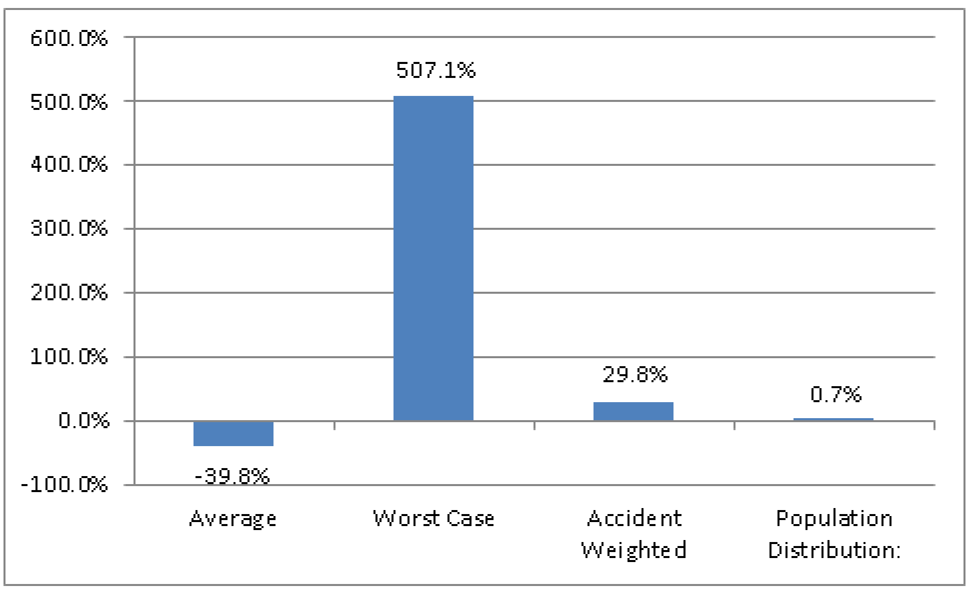


Figure 45: GA Ground Validation Initial Results

To test the validity of the results, an experiment was conducted with a null hypothesis that the mean of the results of the Monte Carlo simulation and the actual value for historical fatality rates are the same value. When compared to the actual value for the GA casualty rates of 0.084 casualties per million FH, the sample data from the experiment demonstrates a p-value of 0.71719 for a two-sided t-test. This result demonstrates that it is plausible that the model results are consistent enough with the actual casualty rates from historical data and there is no reason to reject the null hypothesis that the mean of the model casualty results is the same as the historical data value for casualties [180].

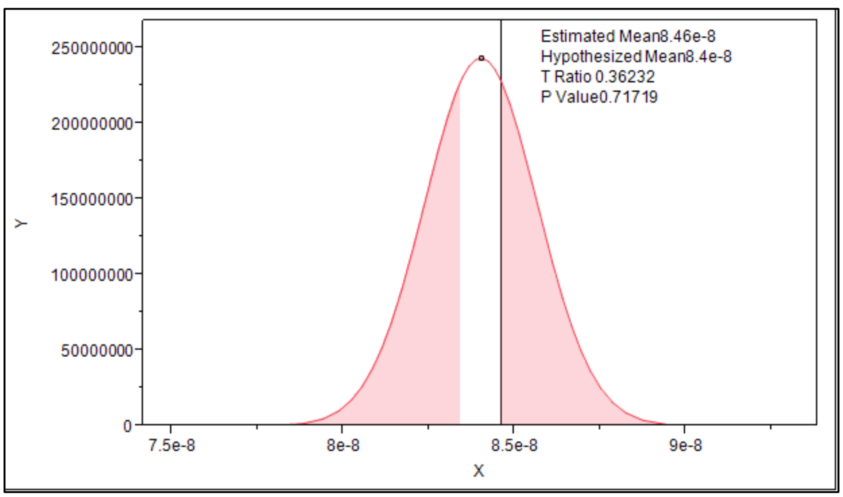


Figure 46: Mean Test for GA Validation

Air Carrier Validation

In an effort to have another way to compare the results of the ground risk model with actual data, data for Air Carrier accidents and fatalities was obtained. The purpose of choosing Air Carrier data, or flights operating under FAR Part 121 was to test the ground model using much larger aircraft than those used in the GA validation process to determine if the model would hold up for larger, heavier airframes.

Gathering the information for this validation effort was slightly more difficult because of the various ways that aircraft are categorized. The aircraft itself is categorized based on the certification standards used, but the accident and incident data is typically categorized by the Federal Aviation Regulation the aircraft was operating under when the incident occurred. However, information on Air Carrier accidents under 14 CFR Part 121 was available with sufficient information to derive third-party deaths. The most relevant data used for the Air Carrier calibration appears in Table 23. The values for serious accidents were obtained by examining the accident rate for all those accidents where any type of fatality occurred. This method was required since the statistics in question for this table also listed minor accidents that would not have necessarily resulted in a major crash or destruction of the aircraft.

The ground fatality rate was derived by comparing the fatalities per accident to the fatalities on board the aircraft for each incident. Finally, a more detailed list of the actual accident reports was obtained and the 14 CFR Part 121 accidents were isolated. While this list was extensive, a sample taken over approximately three years was examined and a histogram of the types of aircraft that appeared in the accidents developed. Using the histogram, an average value for the maximum takeoff weight and size of the vehicles involved in the accidents in question was calculated. The size and weight of the vehicles was required for both the impact area and energy calculations in the model.

Table 23: Data for Air Carrier Validation

Information	Value	Units	Source	Citation
Nationwide Statistics (1992-2010) for Air Carrier Accidents	2.1×10^{-7}	Fatal Accidents per FH	NTSB	[181]
Nationwide Ground Fatality Rate (1992-2010) for Air Carrier Accidents	2.1×10^{-7}	Ground Fatalities per FH	Derived from NTSB	
Average Max Takeoff Weight of Sample of Part 121 Aircraft Involved in the Accidents Cited Above	365,000	Lbs	Derived from Accident Data and Publicly Available Aircraft Information	[182]

The results using three different population density methods appear below in Table 24 and Figure 47. There are only three methods for the Air Carrier validation because the location of the accidents was unavailable. This experiment yielded similar results to the GA validation effort in which the continuous population density distribution and the full ground risk model yielded the best casualty rate predictions.

Table 24: Air Carrier Ground Validation Results

Type of Population Estimate	Predicted to Actual Data:
Average	-47.6%
Worst Case	429.4%
Population Distribution:	-3.3%

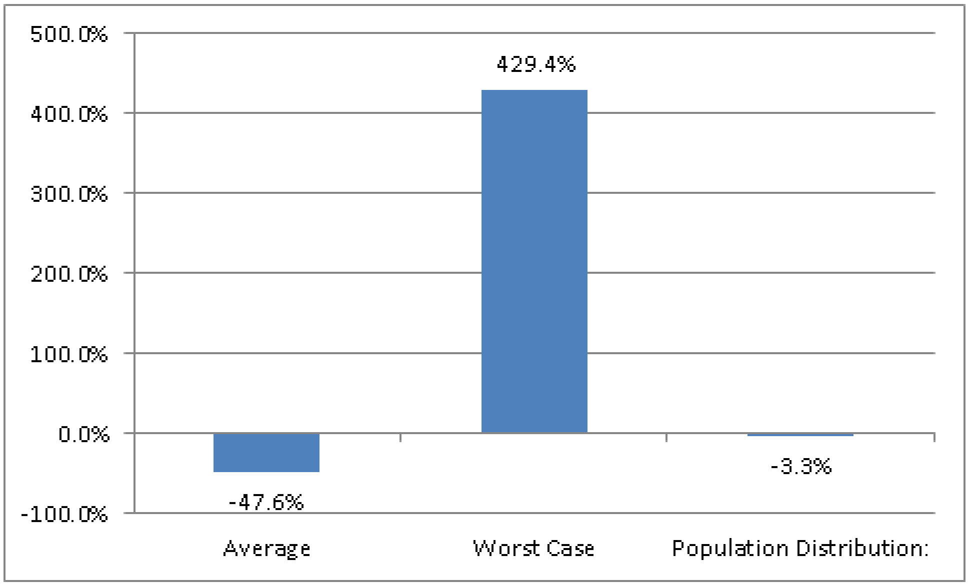


Figure 47: Air Carrier Ground Validation Results Comparison

Once again, one can conduct a test to determine if the mean of the results for ground casualties for the air carrier validation can be considered the same as the actual value for historical air carrier casualties. In this case, the p-value is certainly lower than in the case of the GA validation but still not low enough to reject the null hypothesis if one considers $\alpha=0.05$.

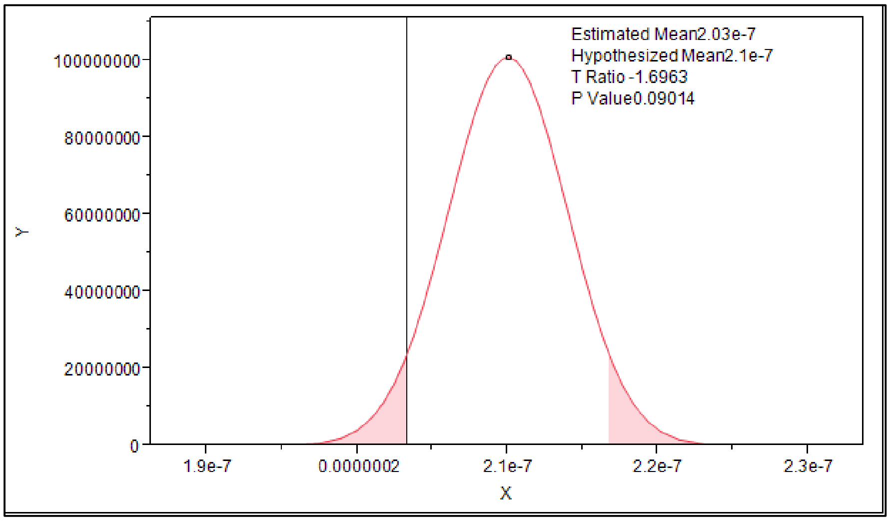


Figure 48: Mean Test for Air Carrier Validation

It is important to review the process and the results above briefly before continuing. The true purpose of this effort is to be able to credibly link system failure rates for UAS to some level of safety for the public. To this point, no method; other than those similar to the simple models described previously, have been proposed. The full ground risk model developed for this effort relies on data and studies from many different sources in an attempt to predict the effects of UAS crashes. Using data from actual accidents with two vastly different types of aircraft, the model was able to predict casualties to within roughly 3% or less than actual deaths. This method offers a credible, accurate way to predict casualties due to UAS operations based on reliability levels and the operating environment. Initially, the hypothesis for Part 1 was that a method could predict UAS casualties to within one order of magnitude of actual data. This hypothesis was based on the belief that sufficient data existed to predict casualties in this manner and that for an initial effort, one order of magnitude would be sufficient to conduct safety analysis. However, after conducting further research into the supporting data used to populate the model, every effort was made to ensure that he model was as accurate as possible. As a result, the final values in the validation efforts are extremely close to historical casualty data.

Sensitivity Analysis For Ground Risk Model

A sensitivity analysis was conducted in which all of the major input variables were varied across a range of values typical of the values found in the real world. For example, the system failure rates were based on current UAS failures, UAS weights were based on the current range for air vehicles, and population densities were based on a typical range from Census values.

The regression coefficients and mapped values for the ground model appear in Figure 49 and Figure 50, respectively. For the ground risk model, the major input variables that affected ground casualties were the weight of the air vehicle, population density, the vehicle failure rate, and the factor that determines the impact area based on vehicle weight. This factor was varied within the range determined by the regression analysis done in this research on impact area and the values presented by Ale and Piers in their study.

In the model, the weight of the air vehicle affects the impact area so all of these variables essentially determine how many people are at risk, how often they are at risk, and how large of an area the vehicle affects. The air vehicle weight also affects the amount of kinetic energy the vehicle carries.

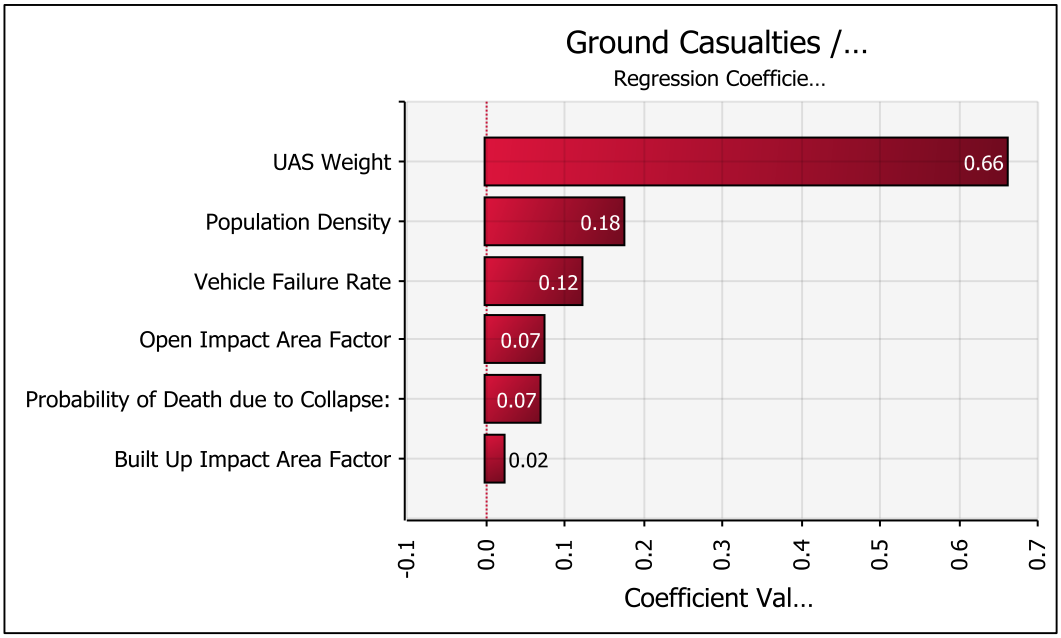


Figure 49: Sensitivity Analysis for Ground Casualties (Full Range)

The mapped value coefficients in Figure 50 show that only a change in the UAS weight parameter by one standard deviation affects the ground casualties to a value on the order of 10^{-5}. All of the other variables only affect the response at one order of magnitude less. This conclusion will be an important one in the Conclusions section when discussing certification strategies and the way forward for UAS airworthiness and certification.

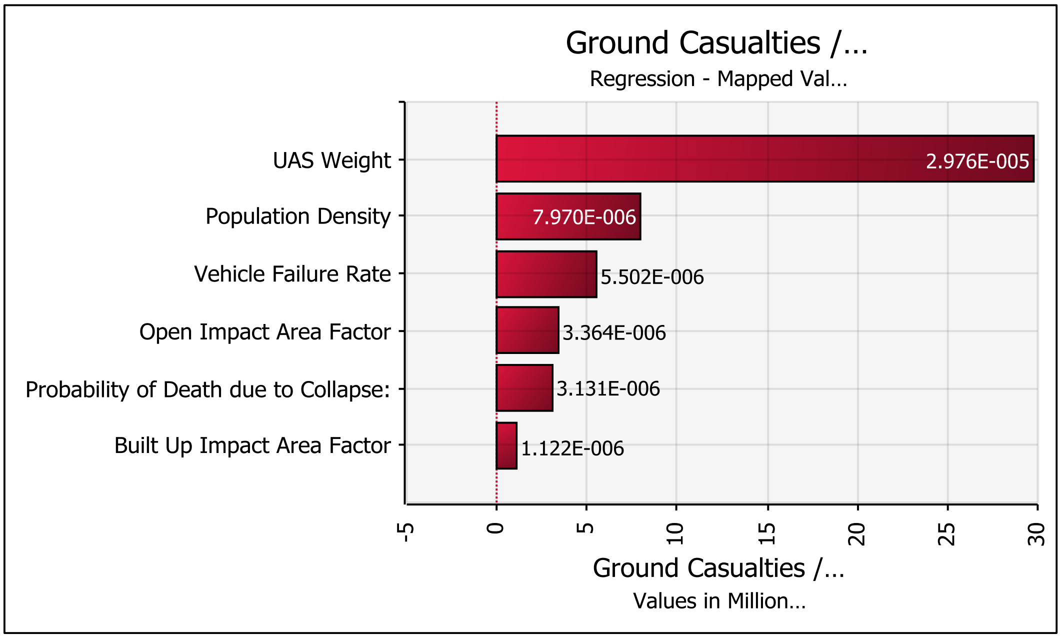


Figure 50: Sensitivity Analysis for Ground Casualties w/ Mapped Values (Full Range)

Air Risk Model

In the second stage of this part of the process a model was developed to predict the risk to second-party persons due to midair collisions. In order to predict the risk of integrating UAS from air to air collisions, one needs a way to model the possibility of a UAS encountering other aircraft in the airspace and then the probability of those two aircraft actually colliding. Then the user must determine how many casualties occur as a result of that collision, if any. A more detailed description of the modeling effort and details of those values will be explained in greater detail below. However, it is first important to explain the general model used to predict UAS to aircraft encounters.

The key requirement for the Initiating Event in the Air Risk model was being able to predict air to air collisions using a method capable of being incorporated into the event tree format. The method had to be able to predict how often a UAS would come into close contact or a Near Mid Air Collision (NMAC) with other air traffic based on parameters such as the size of the UAS, speed of the UAS, speed of other traffic in the airspace and the number or density of aircraft in the airspace.

One method in use for such predictions is the gas dynamic model or gas particle model. Mentioned in articles dating back into the early 1960s for use with air traffic analysis [183], the gas dynamic model attempts to replicate the random motion of gas particles in an enclosed space. According to May, the technique was originally formulated in the early 1960's in an effort to reorganize Swedish airspace [141]. A British report to their Ministry of Aviation around the same time frame also used the gas model technique to try to mathematically validate the separation standards in use at the time [184].

Another early article that appears on this topic was published in 1970. The author, Alexander commented on how the model correlates to work done at the time by the Department of Transportation's Air Traffic Advisory Committee. The paper points out that the model has limitations, most notably in modeling specific air traffic scenarios. However, the advantages of this approach are its simplicity, and the fact that it provides a upper bound of the number of encounters that would occur with no intervention [185].

The gas particle model was also used in the late 1960's and early 1970's by the Department of Transportation to predict encounters in a terminal area [186]. Used in a report prepared for the Air Traffic Control Advisory Committee (ATCAC) in 1969, the gas model, although not explicitly referred to as such was used to determine an upper bound on the potential collisions and course changes in a terminal area to help predict controller workload [187]. The ATCAC was a committee formed in the 1960's by the Department of Transportation whose work formed the basis of the air traffic control system in the United States from that period through the 1980's [188]. A derivation of an encounter prediction model based on the principles discussed above appears in the 1970 proceedings of the IEEE published by Graham and Orr [189].

More recently, the FAA's Test Center used a concept similar to the gas model to determine vertical separation minima. Using more detailed information from actual flight data, the technique nonetheless used an aircraft 'slab' concept instead of the cylinder and determined encounters when the slab overlapped other aircraft slabs [190]. Several other previous efforts to understand UAS midair collision risk also relied on a form of the gas collision model to predict encounters to include Waggoner [90], Weibel and Hansman [115], and discussed by Dalamagkidis [114]. While the details behind the use of the model will be explained later in this paper, the basic premises are that the aircraft in a control volume are modeled as randomly moving particles, as depicted in Figure 51.

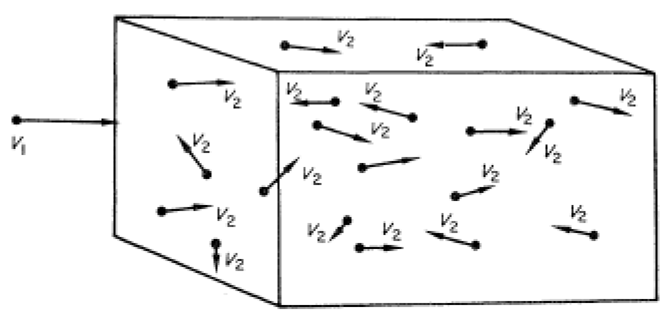


Figure 51: Depiction of Random Particle Motion [141]

Since the aircraft in the volume are small compared to the volume itself, they are assumed to be points in space. Those points are assumed to be stationary with their motion compensated for by determining a relative velocity between the aircraft and question and the other aircraft in the volume. The aircraft in question is modeled as a moving cylinder that sweeps through the volume based on a relative velocity between itself and the motionless particles [141]. An example of that moving cylinder appears in Figure 52

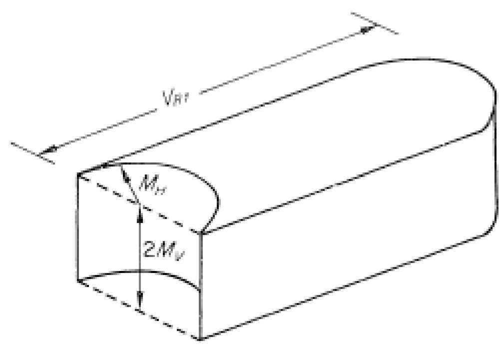


Figure 52: Example Aircraft Cylinder [141]

There are several modified versions of the model useful for specific situations such as flight along airways, intersecting flight across airways or other particular scenarios. However, for the purpose of this research, given its overall statistical nature, the random motion of particles replicated by this model was favored. While this model is less realistic around airports or along airways, it provides a good statistical representation of overall activity in the NAS. In fact, with the advent of trajectory-based operations (TBO) in the near future under NextGEN, aircraft behavior will actually more closely resemble random trajectories and rely less on more ordered trajectories focused on ground-based navigational aids [191].

Finally, the model could be used to examine the impact of various concepts of operation on the safety rates. While the eventual goal of the community is full integration, there are different ways to achieve that in terms of automation levels, operation in controlled or uncontrolled airspace and more.

The Air Risk Model has to account for the number of casualties to other airspace users as a result of UAS operations that could cause midair collisions. This model is slightly simpler than the ground risk model previously discussed. The basic principle used to determine the casualty rate appears in Equation 7. The main components are the rate at which a UAS would potentially encounter another airspace users, the probability that the two aircraft in question cannot avoid a collisions, and the number of casualties caused by that collision.

$$E_c = Encounter\ Rate * (1 - P_{avoid}) * Casualties/Collision$$

Equation 7

<u>Initiating Event (Encounter Rate)</u>

The encounter model used for this research was a variation of the gas dynamics or gas particle model. This was one of the simplest ways to generate an encounter rate that could then be used to propagate the air risk event trees. The encounter rate basically determines how often a UAS would have the opportunity to come in close contact or encounter another aircraft. This rate is the starting point for the process, similar to how the vehicle failure rate was the initiating value in the ground risk event tree.

The fundamental equation to determine the encounter rate appears in Equation 8. The terms in the equation are traffic density (ρ), the horizontal dimensions of the encounter cylinder (H), vertical dimensions (V), and the relative velocity of the air traffic (V_{Rel}). The derivation of this equation can be seen in detail in the reference by May [141].

$$Encounter\ Rate = 4 * \rho * H * V * V_{Rel}$$

Equation 8

In this equation, the traffic density was varied to reflect the different possibilities for air traffic throughout the NAS. The horizontal and vertical encounter cylinder dimensions were based on the wingspan of the unmanned air vehicle. Finally the relative velocity values were represented in the model as a probability distribution which was generated by a Monte Carlo simulation. In the simulation, the closure angles of any two aircraft were represented as a Uniform Distribution between 0 and 360 degrees since in an unspecified section of airspace, aircraft were equally likely to be traveling in any direction.

Representative airspeeds for UAS was already discussed and outlined in Table 7. The other piece of information required to generate relative velocity data was the expected velocities of other aircraft in the NAS. While it is possible to research existing aircraft of various categories and determine their maximum speed or cruising speed, that method does not necessarily reflect the actual speeds that these aircraft use when operating in the NAS. The actual speeds are a reflection of airspace restrictions and weather conditions. To determine more realistic values, it was possible to return to the MIT studies that utilized vast amounts of radar data from the NAS. The data was summarized in a report and could be represented as a triangle distribution of airspeeds. The values used appear in Table 25. In addition, the traffic density values from the radar reports are featured in this table as well in the representative range used in the model to calculate encounter rate.

Table 25: Relative Velocity Simulation Data

Information	Value	Units	Source	Citation
Traffic Speeds	*Triangular Distribution:* Min: 50.36 Peak: 100.72 Max: 302.17	knots	Average of Radar Reports	[142]
Traffic Density	$0.01 - 1 \times 10^{-8}$	acft / nm^3		
Relative Velocity with Intruders	141.92+0.01 * Weight	knots	Regression	N/A

A simulation to determine relative velocities was run in @Risk varying UAS velocities, other traffic velocities, and random encounter angles. The resultant relative velocity was based on a geometric relationship which appears in Equation 9. The relative velocity (V_{REL}) is based on the velocities of the UAS and manned aircraft (V_1 and V_2) and the angle between the two aircraft (δ).

$$V_{REL}{}^2 = V_1{}^2 + V_2{}^2 - 2 * V_1 * V_2 * \cos(\delta)$$

Equation 9

Once the Monte Carlo simulation was run and 10,000 results were developed it was possible to compare the relative velocity values against the UAS weight so that all of the major parameters required to understand the air risk were a function of UAS weight. The result of that regression also appears in Table 25.

Operating Environment

Progressing back to the left side of the air risk event tree, the first determination is whether or not the airspace is under Instrument Flight Rules (IFR). This is an important consideration because under IFR rules, aircraft are not generally responsible for their own separation. The assumption is that aircraft operating under these rules cannot see other aircraft due to weather conditions. As a result, it is the responsibility of controllers to separate aircraft. Table 26 shows the statistics that were used to determine the probability of moving along the IFR branch of the event tree. These values were generated from actual NAS user statistics.

Table 26: IFR Statistics for the NAS

Information	Value	Units	Source	Citation
Proportion of VFR Time in NAS	*Normal Distribution*: Mean: 83.6 Std Dev: 8.8	%	Aggregate NAS Statistics Paper	[192]
Proportion of IFR Time in NAS	*Normal Distribution*: Mean: 16.4 Std Dev: 8.8			

Following the upper branch of the event tree, after the determination of IFR flight has been made, the next branch is whether adequate separation occurs. This is a function of how effective the controller is at maintaining aircraft separation. This probability can have many determining factors based on the type and amount of traffic, human factors, and a number of unique situations. To determine the probability that a controller will maintain adequate separation requires using known values in an educated manner.

First, the FAA publishes system reliability standards for their architecture. A critical system is required to have a reliability of 0.99999 or one failure every 100,000 cycles [68]. This takes into account the air traffic control system, but not the possibility of human error or errors on the part of the aircraft instrumentation that would affect proper separation. International standards for midair accidents due to air traffic control are 1.55×10^{-8} per flight hour [134]. This represents an extremely high level of reliability and effectiveness. Statistics for a 10 year period in US airspace indicate that only 10 midair collisions occurred as a result of air traffic control issues, which when taken against all of the flights that occurred in a 10 year period, represents an almost negligible amount [133]. As a result, for the purpose of this model, the author very conservatively assumed that separation would be assured 99.99% of the time when under IFR circumstances.

Moving back to the lower portion of the event tree, the next step is to examine the non-IFR branch of the tree. As in the IFR case, if an aircraft operated in Controlled airspace there is a high probability that separation is maintained. However, if the aircraft are operating in uncontrolled airspace or if separation is not maintained in controlled airspace, then the avoidance branch of the tree is activated.

Collision avoidance is also a complex scenario that depends on multiple factors. Avoidance can be visual, active and electronic, or passive and electronic in nature. Success depends on the angle of approach, closing speed, the accuracy of position reporting devices, the skill and alertness of the pilot in the manned aircraft and the size of the aircraft involved, among other things. Despite the complexity of this aspect of the air collision risk model, it is important to reflect avoidance as accurately as possible since this area represents one of the most controversial and well researched integration topics.

For the purpose of this model, the probability that two aircraft will avoid is based on a layered approach that also allows for the inclusion of mitigation measures later in the modeling and simulation process. In this section, only the first layer of avoidance or visual avoidance will be discussed. Later in the section that covers mitigation measures, the other layers will be addressed in detail. This layered approach to the event tree mirrors the actual layered approach to safety which the NAS is built upon as depicted in Figure 53.

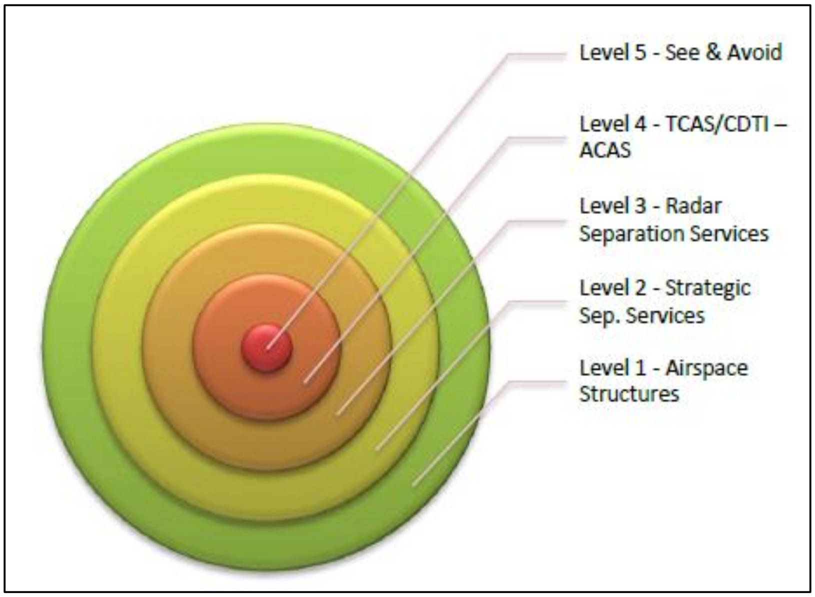


Figure 53: NAS Safety Layers for Avoidance [193]

Visual avoidance of other aircraft is a topic that has been studied in detail. There are studies dating back over half a century that quantify the probability that a pilot would see another aircraft either to avoid that aircraft or in the case of some military studies, to attempt to engage that aircraft in air to air combat. Regardless, there is data available to quantify the probability of aircraft detection. Since this model deals with only one piloted aircraft, the fact that only one of the two parties was using visual detection means had to be taken into account.

The aforementioned article on midair collisions by May cites figures from the Swedish Air Traffic Control Commission that quantifies the probability of avoiding a collision, given than an encounter has occurred. The values, which are featured in Figure 54, depend on whether the aircraft in question are military, domestic (commercial) and general (general aviation). The differences in values reflect the average cruising speed of the different categories. For the type of traffic used in this model, the lower three values of either 75% or 85% would be most appropriate.

Type of conflict	Percentage of conflicts avoided
Military/military	20
Military/general	20
Military/domestic	20
Domestic/domestic	75
Domestic/general	75
General/general	85

Figure 54: Probability of Avoidance Values [141]

Another study conducted for the FAA in the 1980's also looked at See and Avoid effectiveness based on closure rates. The pertinent results of the study appear in Figure 55. The probability of not only detecting but avoiding another aircraft, given an encounter range from 97% for lower closing speeds to as low as 47% for the highest closing speeds.

Closing Speed (knots)	Potential Conflicts (within 250 feet)	Actual Conflicts (within 250 feet)	Probability Detection	See and Avoid Effectiveness
101-199	31,968	942	0.842	0.97
200-299	9,705	1,203	0.670	0.88
300 399	2,401	634	0.524	0.74
400+	948	501	0.320	0.47

Figure 55: See and Avoid Effectiveness [127]

An earlier article that used NMAC data from 1968 and simulations to estimate the effectiveness of see and avoid rated the probability of avoiding a MAC at 95% if the closure rate was less than 100 knots and as low as 32% for speeds over 400 knots. Based on average values of closure rate based on the simulation, the SAA effectiveness is approximately 85%, according to the study [194]. The SAA values are based on the visual probability of detection. These values are corroborated by another study done on the visual detection of Civil Aircraft, the results of which appear in Table 27. The reason for the range in values in Table 27 is that the study in question demonstrates a range of visual detection probabilities based on a pilot scanning all of the time, two-thirds of the time and one-third of the time in the cockpit. The ends of the range represent all of the time and one-third of the time. All of these values did not take into account the proliferation of pilot warning indicators such as Mode S Transponders or TCAS, but they also assumed that both aircraft were trying to see and avoid, not just a manned aircraft and a potentially unaware UAS.

Based on all of these studies and factors, the air risk model used an avoidance probability corresponding to the values in Figure 55 and correlated the effectiveness to the relative closing speeds in the simulation. In situations where the UAS also had some form of SAA capability, the effectiveness of that situation will later be factored into the probability that an encounter would or would not result in a collision.

Table 27: Pilot Avoidance Data

Information		Value	Units	Source	Citation
Probability of Pilot Seeing Other Aircraft	100 knot Closure Speed	72.3 - 100	%	Aviation Medicine Article	[195]
	200 knot Closure Speed	30.2 - 90.7			
	300 knot Closure Speed	16.2 – 48.7			
	400 knot Closure Speed	9.2 – 27.6			
	500 knot Closure Speed	5.0 – 15.0			

Studies have been conducted on the effectiveness of electronic avoidance such as the Traffic Alert and Collision Avoidance System (TCAS) by the MITRE Corporation for the Department of Transportation. The report lists the effectiveness percentages of TCAS avoiding collisions based on varying levels of equipment usage. The report states that TCAS is capable of reducing the number of NMACs that would be unresolved to as little as 5.3% of those that would occur without any TCAS. However, that requires all aircraft in question to be equipped with both TCAS and Mode C altitude reporting equipment [123]. This study was conducted in 1983 so is slightly dated at this time.

Another study by Kochenderfer, et. al. [101] published in 2010 cites risk ratios or the probability of a MAC still occurring, given an encounter for air vehicles with varying levels of TCAS compared to all aircraft with no TCAS. For both aircraft equipped with a newer version of TCAS, the risk ratio is 9.6%, slightly higher than the values published by MITRE. However, both of these reports provide a comparison to use later in the conclusions section of the paper when discussing SAA effectiveness.

Effects

One of the more difficult areas to model in the midair collision risk events is what actually occurs if an air vehicle strikes another aircraft. The effects can vary based on where the air vehicle strikes the other aircraft, the exact materials present on both aircraft, the angle and speed at which the strike occurs and which, if any, vital components the strike affects. As was the case with striking a building on the ground, a simplified method to capture the effects of a midair collision needed to be developed.

For smaller unmanned aircraft impacting a manned aircraft, the closest approximation would be that of a large bird strike. Federal Aviation Regulations do not specify any requirements to withstand a bird strike for any fixed-wing aircraft category other than those covered by Part 25. 14 CFR Part 25.631 specifies a requirement for continued safe flight and landing after striking an 8 pound bird at V_c , or cruise speed at sea level [20]. This would seem to imply that larger aircraft could at least manage to survive collisions with the smallest of unmanned vehicles. However, the density and composition of a bird, given their extremely fragile bone structure may not be a good representation of an unmanned vehicle.

A better way to compare the potential damage caused by a strike would be to look at the kinetic energy equivalent of a bird strike and compare that to a potential unmanned vehicle. A report for the EASA depicted the design points for aircraft bird strikes based on kinetic energy using the range of airspeeds these aircraft listed as their cruise airspeeds. The chart from that report appears in Figure 56. Obviously, the highest threshold would be for Part 25 jet aircraft because of their higher cruise speeds. However, a four pound air vehicle that strikes another object with a 400 knot closing speed would generate over 28,000 ft-lbf of energy or over 38,000 Joules. This falls in the range of the CS-25 damage threshold and above the range of all of the other aircraft which means that even such a small unmanned aircraft could cause catastrophic damage.

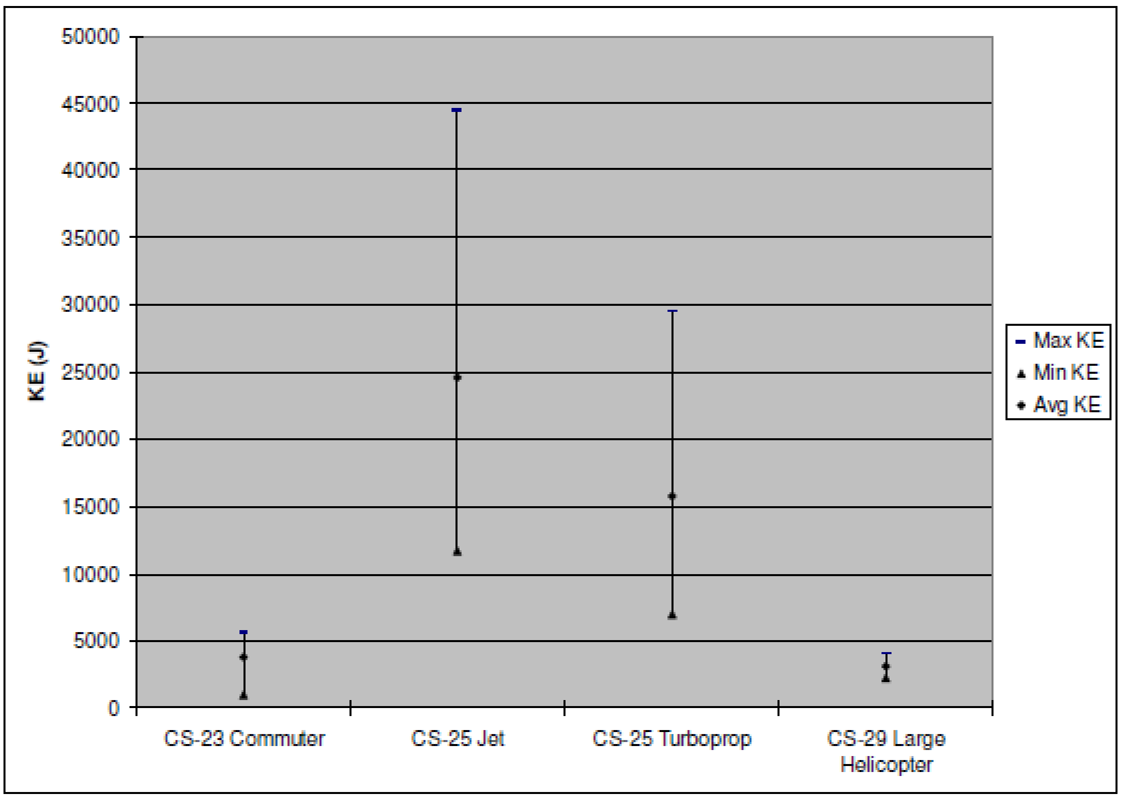


Figure 56: European Bird Strike Standards [196]

Yet another way to look at this problem is to look beyond bird strikes and examine debris damage to aircraft. The Range Commander's Council published information on the potential for damage to people, aircraft and watercraft due to explosions or the breakup of missiles and spacecraft. In a document on risk in areas surrounding range activities, objects with as little weight as 0.66 pounds are considered capable of producing a fatality on an aircraft [197]. The same document, using experimental data, lists the threshold energy required to penetrate an aluminum roof at only 17 ft-lbf. Many aircraft have an aluminum skin or use materials with similar properties and this paper has already shown that even a small unmanned aircraft crash would impart well more than 17 ft-lbs of kinetic energy.

After examining these reports, the assumption used to determine the effects of a midair collision was that any collision would be catastrophic to all manned aircraft with the exception of jet Transport or Air Carrier aircraft. If the UAS encountered one of these larger aircraft and the energy inherent in the UAS crash was lower than the lowest energy threshold for a Transport category jet aircraft (approx. 7400 ft-lbf), the crash was deemed survivable. If the energy fell above this threshold, the impact was considered catastrophic. This was simply the only way to reasonably and conservatively account for the potential casualties caused by any collision. To determine the number of casualties, the model took into account a representative mixture of aircraft types and used load factor data to determine the predicted number of passengers on board. The statistics used to support this value appears in Table 28.

.

Table 28: Data used for Midair Collision Casualty Estimation

Information		Value	Units	Source	Citation
General Aviation	Percent of Total Hours	59	%	GAMA Databook and RITA Database	[198, 199]
Air Carrier		41			
Breakdown of Air Carrier Aircraft by Type	Jet	55.0		FAA Factbook CY 10 Data	[200]
	All Others	45.0			
Load Factor for Air Carriers		*Normal Distribution:* Mean: 76.765 Std Dev: 0.457		FAA Statistics	[143]
Passengers per Air Carrier		106.11	People/acft	FAA Factbook	[200]
Energy Absorption for Part 25 Jet Aircraft		10,000	Joules	Bird Strike Report	[196]

The event tree that describes the Air Effects or the casualties that will occur in the event of a MAC appears in Figure 58. This figure continues the event tree from Figure 57 when any of the blocks in that figure terminate with the term Air Effects.

<u>Air Risk Event Tree</u>

The event tree to account for the risk of a midair collision appears in Figure 57. The major assumptions associated with the model are listed below.

- The aircraft type composition (GA, Commuter, etc.) is based on number of hours logged in NAS by aircraft type.
    - All intruder aircraft are either GA, Transport or Commuter categories.

- There is a uniform airspace density in a given volume.
- The vertical speeds of aircraft are neglected.
- The diameter of the frontal area of the encounter cylinder swept out by the UAS is based on the UAS wingspan. This approach is consistent with encounter models used by the FAA [85].
- Visual avoidance percentages are based on closure rates
- There are roughly 1.76 fatalities per MAC with General Aviation (data-based)

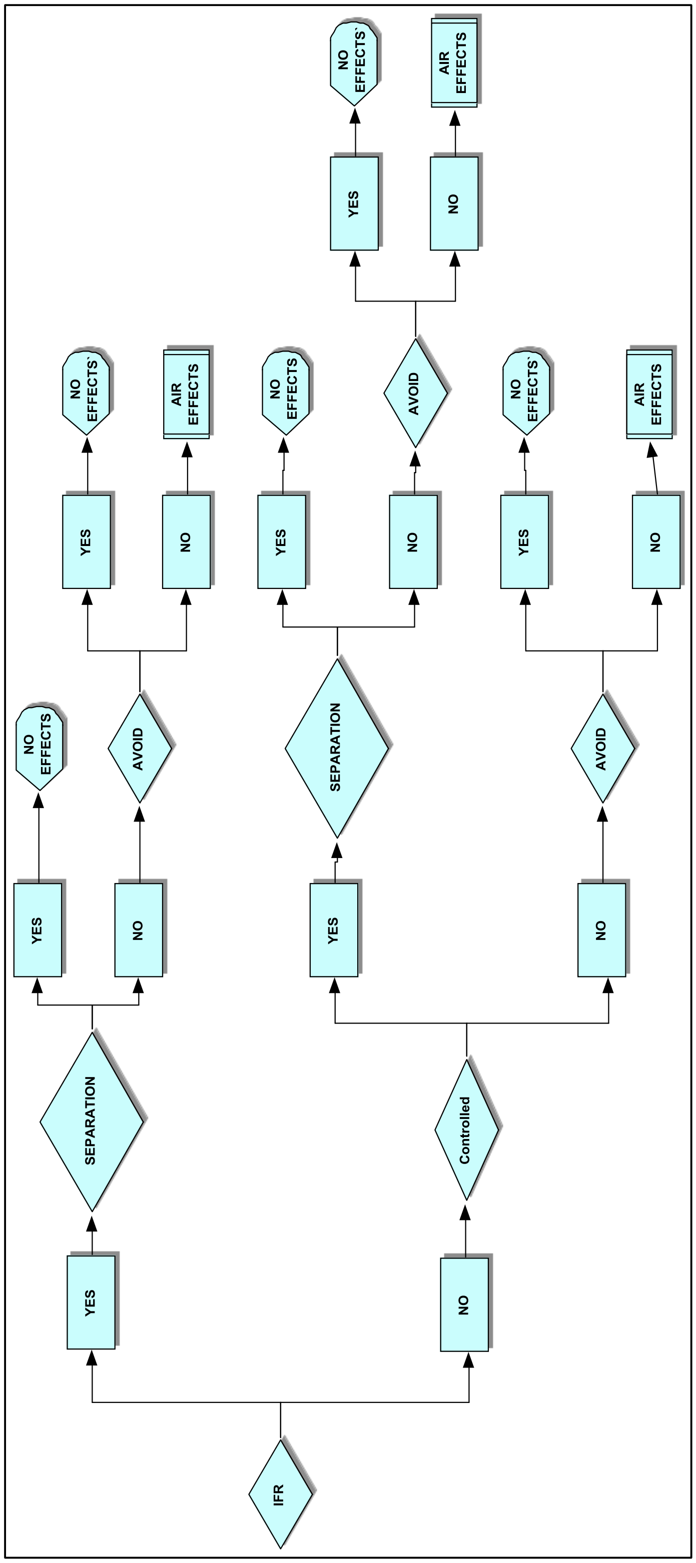


Figure 57: Event Tree for Air Risk

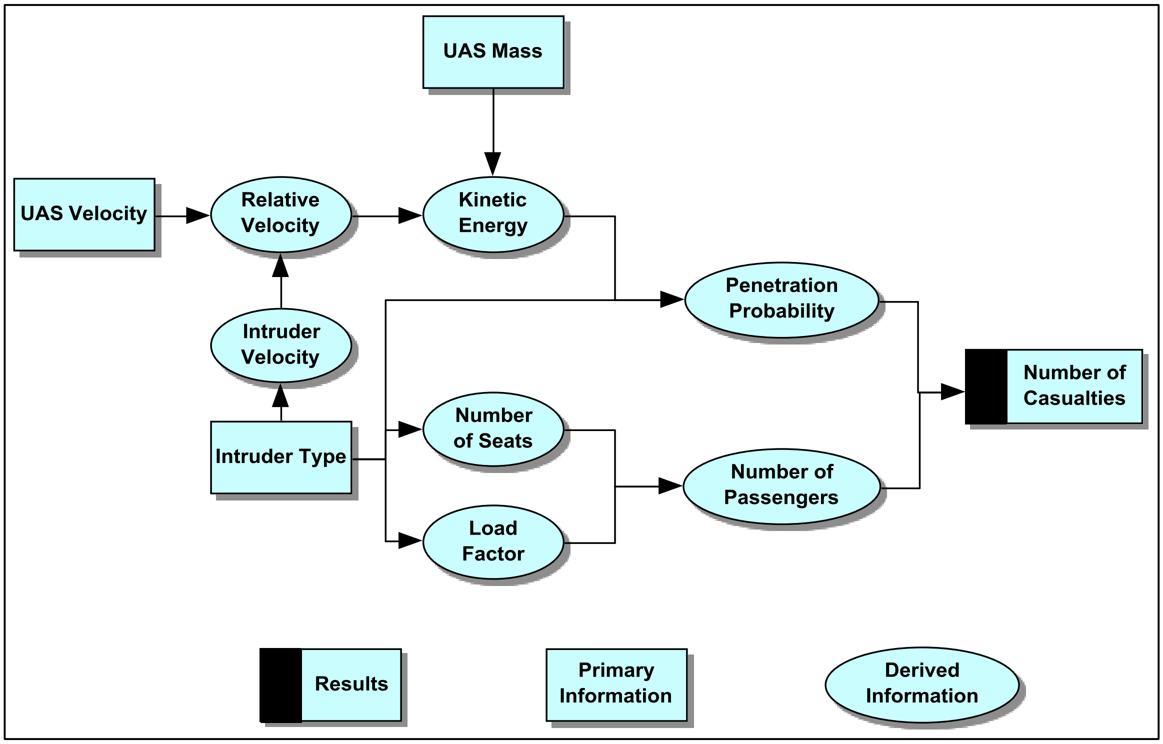


Figure 58: Air Effects

Another summary of the major parameters involved in the midair collision risk model also showing how this model approached those parameters appears in Table 29.

Table 29: Air Risk Model Parameter Review

Model Parameter	Waggoner	Dalamagkidis	Weibel	Current Thesis
Encounter Model	Gas Model	Gas Model	Gas Model	Gas Model
Avoidance	Derived from Historical Data	Derived from Requirements	N/A	Based on Reports from Visual and Electronic Avoidance Studies
Effects on Aircraft	N/A	N/A	N/A	Energy-Based. Data from Certification Requirements and Bid Strike Studies
Casualties	Based on Passenger Estimates	N/A	N/A	Based on Passenger and Load Factor Data
Validated	No	No	No	Yes, Using Historical Data

Air Risk Model Validation

If the population density was an important variable in the ground risk model, the aircraft density was also an important variable in the air risk model. This variable accounts for the amount of aircraft per airspace volume. Once again, GA statistics were used to validate the model. However, unlike the census statistics for the population density on the ground, statistics on aircraft density were not readily available. As a result, for the air model a reasonable estimation of airspace density had to be developed.

To generate an airspace density relevant to the time period that the accident statistics were obtained from, the author used data from the National Transportation Safety Board (NTSB) to determine the average annual flight hours that aircraft in the Air Carrier, Commuter, Air Taxi and GA categories reported. In addition, the Census data described above was used to determine the total U.S. land area. This area was converted to a volume by multiplying by 5,000 ft and 35,000 ft for GA aircraft and all other aircraft, respectively. The rationale behind those values was to examine the altitudes that those type of aircraft typically operate within. To determine the average aircraft aloft at any given time, the annual flight hours for each aircraft category were divided by the number of hours in a calendar year. The density values for GA aircraft and all other aircraft were combined to calculate an average aircraft density in aircraft per nm^3. The values discussed in this paragraph appear below in Table 30. To ensure that the value for airspace density is within the range of logical airspace densities, the values from radar reports which appear in a previous UAS study on midair collision risk appears in Figure 59.

Table 30: Data Related to Airspace Volume and Density

Information	Value	Units	Source	Citation
Average Annual Total U.S. Flight Hours for GA	25,396	1000s FH	RITA Database	[201-204]
Average Annual Total U.S. Flight Hours for All Others	19,785			
Average GA Aircraft Aloft	2899	Aircraft / Hour	Calculated	N/A
Average Aircraft Aloft All Others	2258			
Total U.S. Land Area	3,796,742.2	mi^2	Census Data	[147]
Height of Airspace of Concern for GA	5,000	ft	Estimated	N/A
Height of Airspace of Concern for All Others	35,000		Estimated	N/A
Total U.S. Airspace Volume for GA	2,830,685.0	nm^3	Calculated	N/A
Total U.S. Airspace Volume for All Others	16,512,329.4			
Average Airspace Density for GA	1.16×10^{-3}	Aircraft / Nm^3	Calculated	N/A

The other relevant important data used in the air risk validation process appears in Table 31. The information on midair collisions and casualties was obtained from NTSB databases. Information on the intruder traffic speeds, GA average velocity, and GA average frontal profile were derived from previous studies on air to air risk

Table 31: Data Used for Air Risk Model Validation

Information	Value	Units	Source	Citation
Traffic Speeds	*Triangular Distribution:* Min: 50.36 Peak: 100.72 Max: 302.17	knots	Average of Radar Reports	[142]
General Aviation Velocity	173		Waggoner Study	[90]
Vertical Distance (V)	36	ft	Average of Studies and Information on GA Aircraft	N/A
Horizontal Radius (H)	36		Average of Studies and Information on GA Aircraft	N/A
Midair Collision (MAC) Rate for GA	5.9×10^{-7}	Midair per FH	NTSB Data	[114]
MAC Rate for All Aircraft	3.74×10^{-7}			
Fatalities Caused by Midair Collisions	6.82×10^{-7}	Fatality per FH		
Casualties per Midair Collisions	1.76	Fatality per Midair		

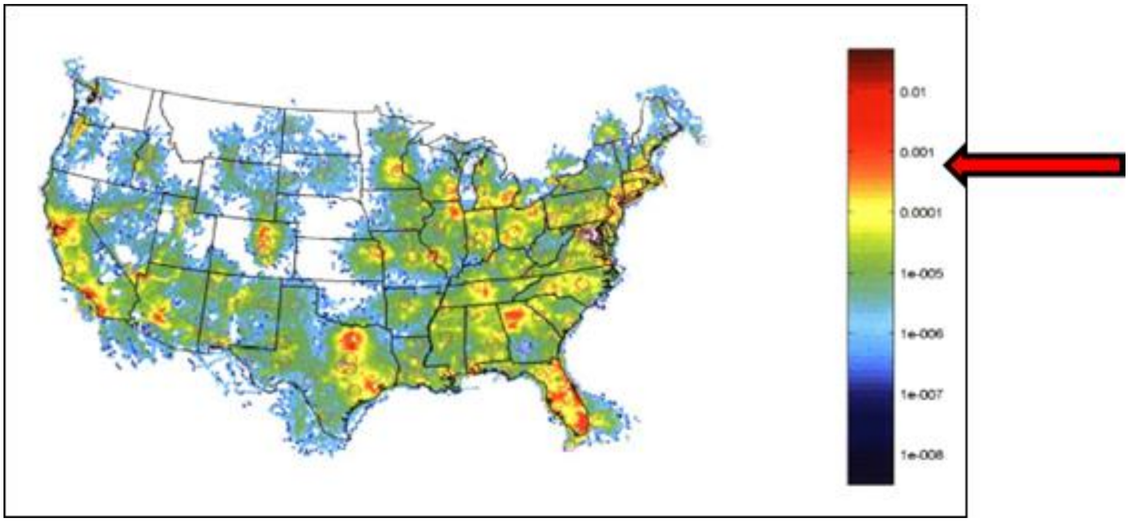


Figure 59: Airspace Densities (acft/nm^3) [102]

Figure 59 from Kochenderfer shows the airspace densities taken from FAA and DoD radar sites in the U.S. for cooperative traffic, or traffic that is using a transponder to transmit location information, but only on Code 1200 or VFR traffic. Based on statistics on the airspace, VFR traffic comprises approximately 84% of the air traffic in the NAS so the data is representative of the total NAS traffic [192].

To help corroborate the calibration data, a graphical depiction of all NMAC and MAC across the United States was used. This information was obtained from a FAA-sponsored and military operated website. The yellow circles represent near midair collisions while the red dots represent actual midair collisions. As one would expect, these incidents are clustered around major population areas. The trace of the yellow areas corresponds roughly to the airspace density values of approximately 0.001 acft/nm3 from Figure 59, or the yellow and red areas in that figure. This additional information provides further corroboration that the air model is reasonable.

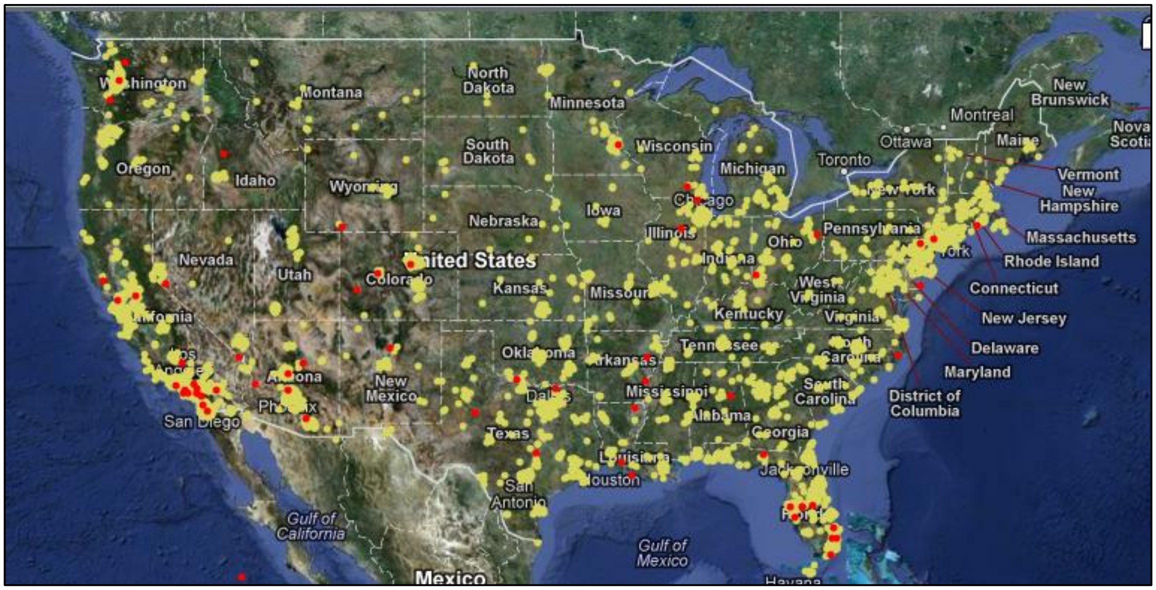


Figure 60: Location of NMAC and MAC [205]

To determine the number of casualties caused by GA midair collisions, the validation effort also incorporated historical data. Using the statistics from prior General Aviation accidents, one is able to determine that for all fatalities resulting from midair collisions, an average of two passengers were on board. The values to support the value of approximately 1.76 casualties per midair collision for GA aircraft appears in Table 31.

. The reason why the number of casualties per collision is so low is that during the entire period in question, the only midair collisions that occurred causing fatalities did not include Air Carrier aircraft. As mentioned earlier, the casualty estimation method for the air risk model as a whole will use estimates of the numbers of passengers on board that include larger aircraft, but for the purposes of calibration the casualty estimation rate was kept at 1.76 per aircraft to more closely replicate the actual data being used for calibration.

The results of the calibration efforts for the model appear in Table 32. They consist of three important metrics and a comparison to historical data for each metric. The historical NMAC rate is based on NTSB data from a representative time period of the calibration effort [206]. The historical MAC and Air Casualty Rates were discussed in Table 31. The results show that the model over-predicts NMAC rates by over four times the historical rate. However, this is not particularly surprising since the encounter model represents random motion and not any form of airspace control measures. In addition, NMACs are typically underrepresented since that statistic relies on pilots first noticing another aircraft in their vicinity and second, reporting the NMAC.

The more important values are the actual MACs, which only differ by roughly 2% from historical data and the casualties which only differ by less than 1%. For a model that is a basic representation of the airspace and behavior of aircraft in that airspace, this provides a fairly good prediction of casualties that will be useful in adding additional realism into the TLS values for later phases of the research.

Table 32: Air Model Calibration Results

Values:	Rates /100k Hr	% Difference
Model Encounter Rate	2.7461	424.59%
Actual NMAC Rate	0.5235	
Model MAC Rate	0.0384	2.72%
Actual MAC Rate	0.0374	
Model Air Casualties	0.0676	-0.86%
Actual Air Casualties	0.0682	

Sensitivity Analysis for Air Risk Model

For air casualties, the two biggest sources of variability are the size of the vehicle and the density of air traffic. Larger air vehicles tend to have more area to generate a midair collision, and the air density plays a large role in the number of potential NMACs. The next three drivers are all related to the operational environment or airspace architecture that the UAS can operate in. This shows that the concept of operations for UAS integration can have a significant effect on safety. The extent to which SAA systems can avert MACs, and the degree to which air traffic management can maintain separation will play a major role in preventing midair collisions and thus casualties.

The speed of the UAS plays a minor role in the air casualties, mainly because the airspeed ranges for UAS still tend to be below manned aircraft at this time so the airspeeds of the manned aircraft play a more dominant role in determining relative airspeed. The IFR rate, or extent to which the air traffic is under IFR rules and the degree to which the Air Traffic Management (ATM) system is effective in maintaining separation have less impact on the overall casualty rate. This is not because these two variables are unimportant. The reduced effect on the response is largely due, in this case, because the inputs themselves do not have a large range of variability.

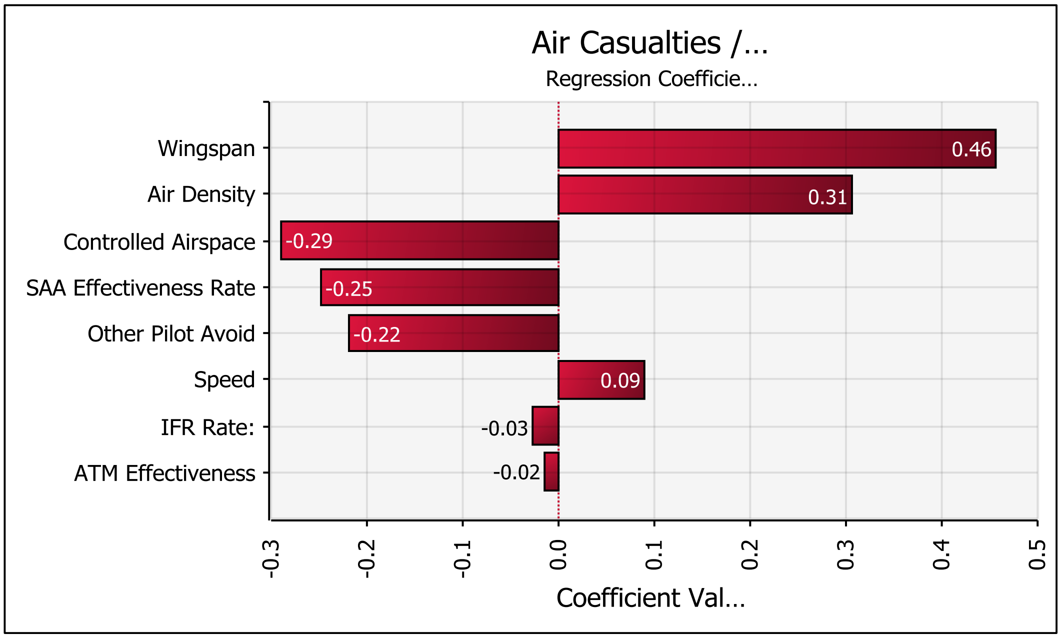


Figure 61: Sensitivity Analysis for Air Casualties (Full Range)

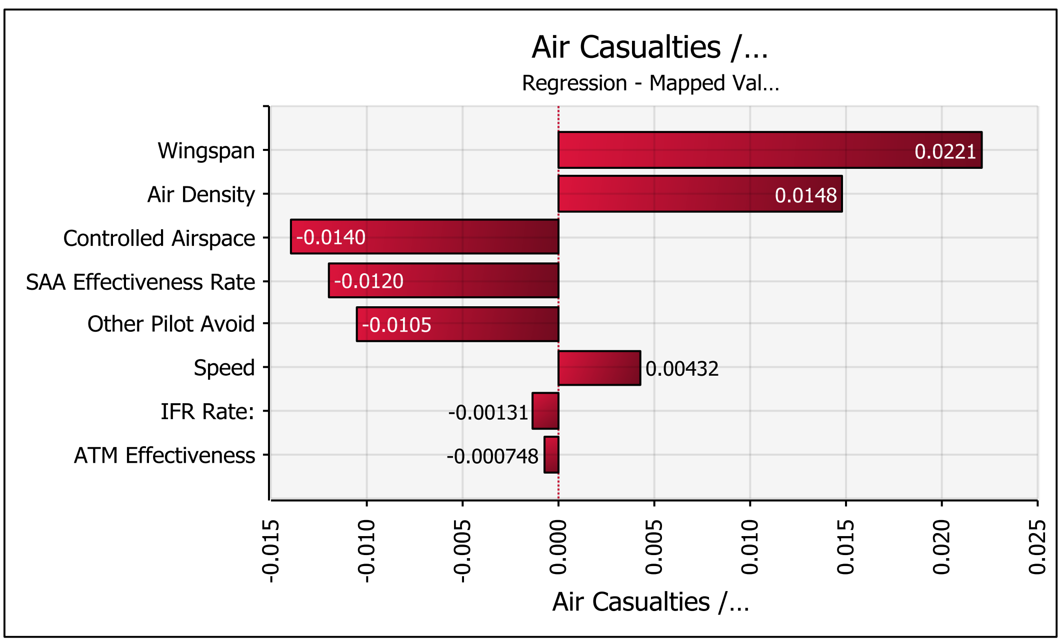


Figure 62: Sensitivity Analysis for Air Casualties w/ Mapped Values (Full Range)

In addition to the sensitivity analysis, another way to examine the importance of the input variables in the model is to compare the various parameters in a scatterplot, as in Figure 63. In this plot, every point represents cases from the simulation. These scatterplots were prepared in the software tool JMP®. The software and scatterplot provide the user with the ability to select an individual data point and analyze the characteristics of that point, in terms of input values and output value.

The tool also provides the opportunity to filter cases that meet specified criteria, a technique known as Monte Carlo filtering [207]. In this particular case, the simulation results were filtered based on casualty rates. The green points represent those cases that are equal to or lower than a casualty rate representing an extremely safe value. What is evident is that the wingspan of the UAS and the density of the intruder air traffic are the two most critical input variables in limiting air casualties. The green or 'safe' data points are predominately located along the lower ranges of these two variables, while they remained scattered throughout the ranges of other variables. This finding has a significant impact in the way in which SAA certification standards should be identified and will be discussed in more detail in Part 3.

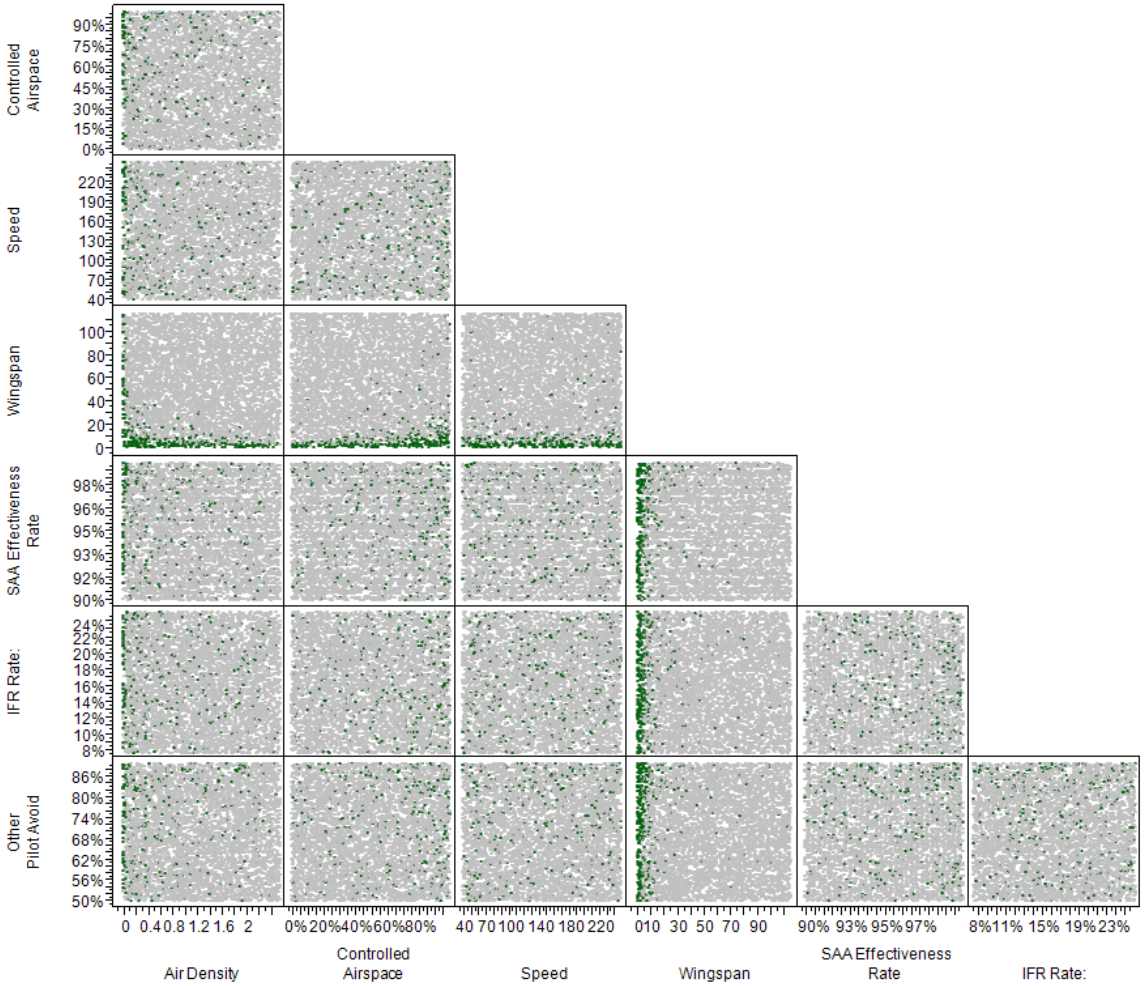


Figure 63: Scatterplot Filtered by Air Casualty Rate

Lost Link Initiation and Effects Model

The last major portion of the model to discuss is to account for casualties caused by link failures. In addition to SAA, the topic of lost link is one of the most discussed areas regarding UAS integration due to its inherent dissimilarity with manned flight. For the purpose of this research, the link encompasses any of the components required to send and receive data to and from the air vehicle to a controlling entity. Thus a lost link incident can mean that a failure occurred with a ground station, a receiver / transmitter on the air vehicle, a space-based satellite or could be due to interference with the transmitted signal itself. How the lost link condition occurs is not relevant to this research, just as how the air vehicle fails to maintain coordinated flight was not a concern in the ground risk event tree.

In the third aspect of this part of the research, the author developed an event tree to model the impact of loss of data link between a controlling entity and the air vehicle. The purpose of this part was to develop a method to analyze the impact of link failures on casualty rates and analyze the effects of various risk mitigation techniques and operational aspects of UAS such as autonomy level has on risk. What makes this event tree model different that either the ground or air risk model is that the lost link model acts as an initiating event to increase either ground or air risk. This will be explained in more detail in the section on the model itself.

While the term lost link can have different definitions, the definition used for this paper was featured in an article by the Air Line Pilots Association (ALPA). They describe lost link as a condition when the operator can no longer control the air vehicle due to a problem with the control station, data link, or receivers on the air vehicle itself [208]. It is important to note that this does not mean that the air vehicle will be unable to maintain flight immediately since most UAS do not take direct flight control inputs from the operator except during landing and takeoff events. This does mean, however, that the operator will be incapable of sending new commands to the air vehicle until the lost link condition is resolved. This has implications for the ability of the system to avoid other aircraft as well as execute continued flight beyond the commands already received by the air vehicle.

Aside from the link failure rate, the other major inputs required to determine the ground and air casualty rates due to lost link are the endurance of the UAS in question, and a new term introduced as the Mean Time To Reestablish link, denoted as MTTR in the event tree. As previously discussed, the endurance term is calculated based on regression data using the vehicle weight as the independent variable.

The MTTR term is similar to the more commonly used meaning which is Mean Time to Repair. Reestablishing link is the same concept as repairing the link. When developing the lost link model, it was quickly determined that the link failure rate by itself was insufficient to determine risk. In the case of a system failure in the ground risk model, once the failure occurs, it was assumed that the vehicle cannot safely continue flight. However, a link failure does not prevent continued flight, it merely prevents further command transmissions to the air vehicle. As a result, the amount of time spent in a lost link condition is important.

The combination of frequency and duration of the disruption of a signal is similar to the problem posed in the electrical power community. An article on electrical power on shipboard applications uses a term Quality of Service to combine the two metrics [209]. Other sources refer to Power Quality or a Power Quality Index. Overall, the failure rate and the average duration of the failure can be combined in a type of Operational Availability metric in the form of the equation below, where the Mean Time Between Failures (MTBF) is the inverse of the failure rate. While the Operational Availability metric could have been used in this framework, it was decided to analyze both the link failure rate and MTTR independently to be able to generate the type of data from Figure 91 in Part 3 that could aid in future tradeoff studies.

$$Operational\ Availability = \frac{MTBF}{MTBF + MTTR}$$

Equation 10

The lost link model, which appears in Figure 64, consists of two, separate event trees. It also does not calculate expected casualties independently. The two trees merely serve to determine a rate at which a lost link event will either cause a ground impact or a midair collision. The actual casualties that would occur due to either of these events are calculated using copies of the air risk and ground risk event trees.

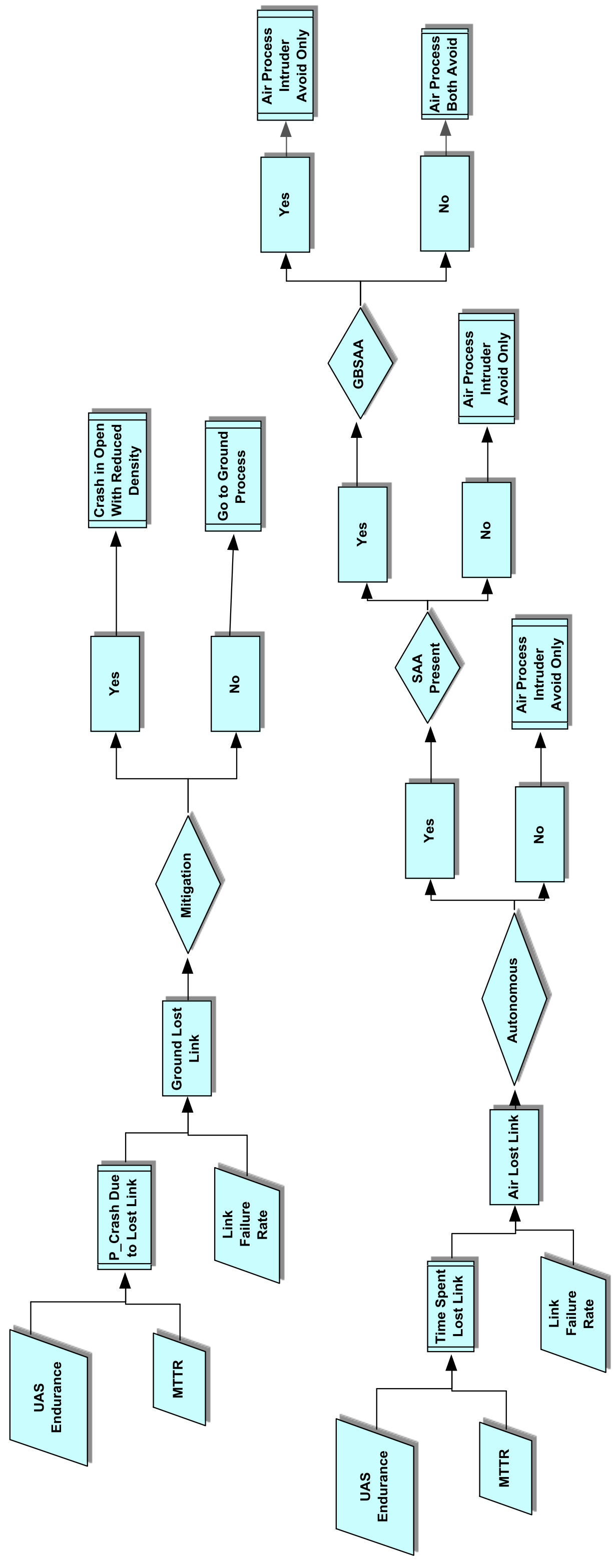


Figure 64: Event Tree for Lost Link Risk

In order to better understand the lost link model, it will be analyzed from left to right. The top and bottom event trees start with the same inputs. A value for the link failure rate is set as an input based on a uniform distribution that covers a realistic range of communications failure rates. Those failure rates, which span a wide range of values, appear in Table 33.

Table 33: Historical Link Failure Rates

Information	Value	Units	Source	Citation
Global Hawk Data Link Failure Rate	505.6	failures/ 100,000 FH	LMI Report	[138]
Predator Data Link Failure Rate	43	failures/ 100,000 FH	MITRE Report	[50]

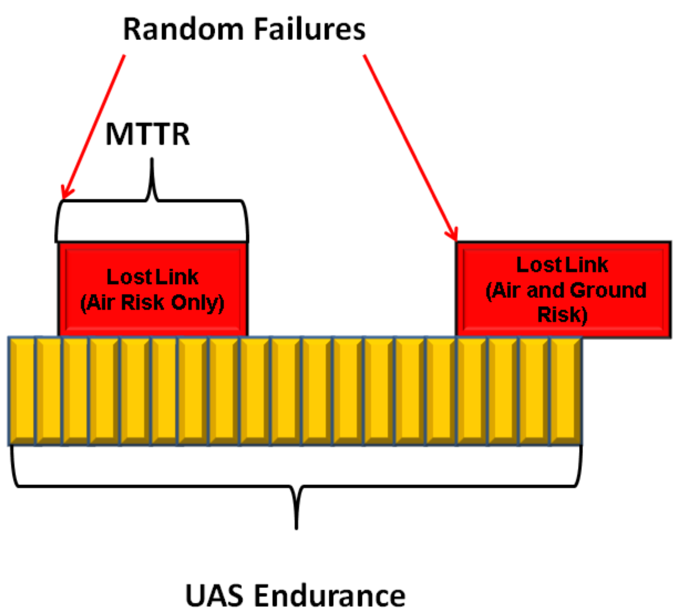


Figure 65: Lost Link Concept

An example of how these terms interact to affect the UAS is depicted in Figure 65. The UAS endurance is depicted as a yellow bar showing how long the UAS could potentially remain aloft. A lost link failure is generated based on the failure rate input variable. The lost link incident is assumed to occur randomly throughout the flight's duration.

While there may be some rationale as to why the lost link would be more likely to occur during a certain portion of the flight; that type of logic would highly depend on the flight profile, which is beyond the scope of this research. For example, one could argue that a lost link is more likely to occur at the midpoint of a mission if the UAS is operating at the furthest distance from the ground station at that time. Assuming a line of sight data link, which is most common at the time of this effort, terrain could play a major role in when a lost link condition could occur. Since this thesis was not based on a particular type of UAS or a particular mission, the decision to model the lost link failure as occurring randomly throughout the mission was more applicable.

Once the lost link event occurs, the MTTR variable also plays a role. This variable was modeled as a uniformly distributed variable that will be analyzed to determine its impact on safety. Based on a known start point of the lost link event, the MTTR, and a known endurance, the simulation calculates two things. One, the simulation calculates how long the UAS will operate in a lost link condition, which affects the additional air to air collision risk rate. The other thing the simulation determines is whether the time to reestablish the link will exceed the remaining endurance of the vehicle. If it does, the operator will be unable to recover the vehicle, leading to additional ground risk due to lost link. The first case is depicted by the red block on the left of Figure 65, and the case of a vehicle that eventually crashes due to lost link is depicted by the red block on the right.

Following the ground lost link, or upper event tree, the only other branch in the tree is whether mitigation measures are in place to minimize the risk to bystanders on the ground. This would come in the form of automatic logic to relocate the air vehicle to a less populated area or in some technology to reduce impact such as a parachute device. The simulation uses binary logic to change the ground risk event tree to alter the effects of a ground crash if mitigation is present. It is assumed that, regardless of the level of autonomy the vehicle possesses, that there will be an ability to execute a pre-determined route or plan in the event of a lost link condition.

A large portion of the lower lost link event tree is comprised of decision points to account for the UAS architecture. The amount of autonomy the vehicle enjoys will determine the amount of risk posed by a lost link event. Autonomy can carry many different meanings with respect to UAS. One article on the topic attempted to formulate a common view of various autonomy levels ranging from fully controlled by the operator to fully autonomous [210]. In the context of this event tree, autonomous implies the ability to take action to avoid a potential air to air collision without intervention from the operator. Whether or not the vehicle can detect those potential air to air collisions in a lost link condition depends on whether any SAA system is integral to the air vehicle or relies on ground sensors. This determination will affect the amount of risk due to a lost link event. Those decisions can be altered by changing input parameters in the simulation spreadsheet.

In summary, the primary assumptions used to populate the lost link event tree model appear in the list below.

- Lost link is equally likely to occur at any time during mission (uniform distribution of failure initiation)
- If the option to go to a safe area is chosen as a mitigating factor, the vehicle will crash in an open area which has $1/10^{th}$ the population density of the current operations area. If not, the will loiter in place and crash over current pop density unless link is reestablished prior to limit of UAS endurance.

Lost Link Model Validation

There was no credible way to compare the lost link model to manned aircraft data since the lost link case is the most different than manned flight. However, there are several factors that mitigate the need for a direct validation or calibration of the lost link model. The lost link portion of the model is simply a way to generate an initiating event. In other words, it is a driver for a failure. However, this failure can cause either a midair collision or a ground impact, depending on the severity of the lost link and the architecture that the vehicle is operating under.

First, the final effects or casualties caused by the lost link conditions both occur in the model in the actual spreadsheets that calculate ground and air risk fatalities. Essentially, the lost link model provides input to either the ground or air model. Second, the lost link model is simply a series of logical events in the event tree that are determined based on variables that are determined randomly in the model. The purpose of this model is not to validate or calibrate the model against actual data, but instead to help determine minimum performance requirements necessary to meet the specified TLS.

Sensitivity Analysis for Lost Link Models

A sensitivity analysis was also conducted for the ground and air casualties caused by lost link conditions. The tornado graphs appear in Figure 66 and Figure 67 below. For the most part, the patterns for which input variables have the most impact on casualty response mirror the analysis for ground and air casualties. The only major difference is that the mean time to reestablish (MTTR) link variable appears in the analysis due to the impact this variable has on how long the system remains in a lost link condition.

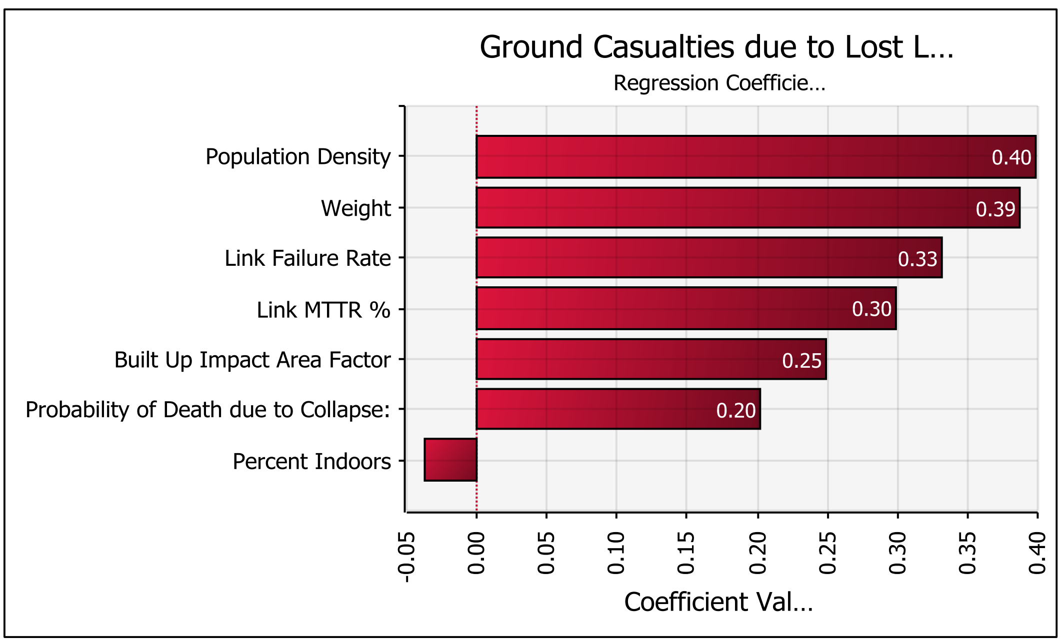


Figure 66: Sensitivity Analysis for Ground Casualties due to Lost Link

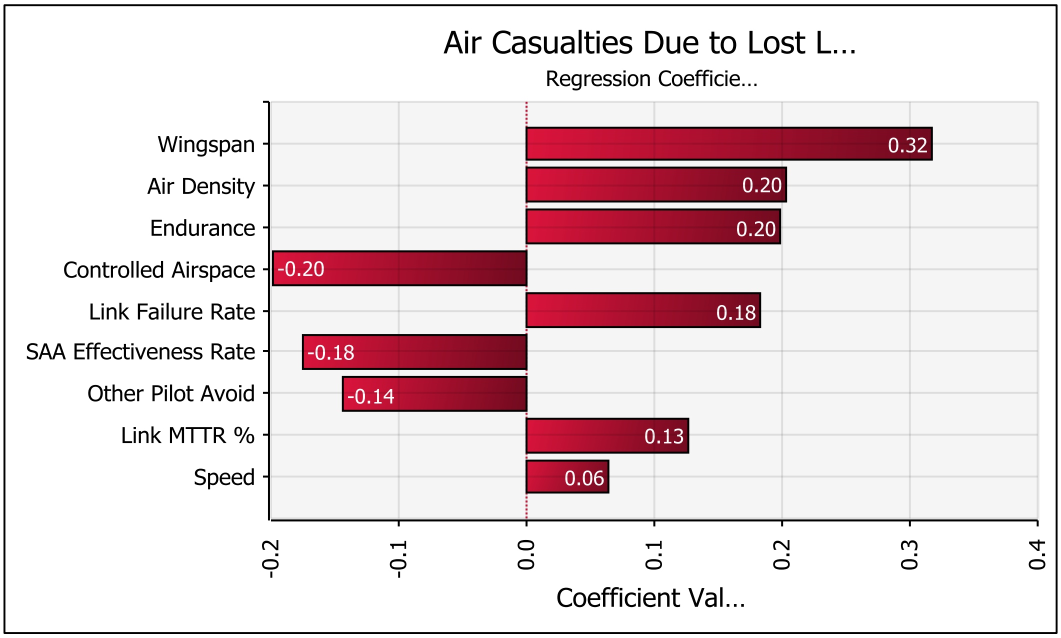


Figure 67: Sensitivity Analysis for Air Casualties due to Lost Link

Because the variability of the responses for ground and air fatalities were dominated to a degree by the weight or size of the air vehicle and either the population or airspace density variables, additional analysis was conducted in Part 3 of this effort. In that section further sensitivity analysis was conducted that corresponded to the three scenarios that are described in more detail in that section. The purpose was to examine if, when eliminating the variability caused by the wide range of UAS weights, and population or air traffic density variables, if additional trends could be observed.

Part 2: Implications of the Framework

Once the gap in the bow-tie diagram was closed by modeling the terminal effects associated with UAS failures, the next step was to determine the impact of having an accurate way of predicting UAS casualties would have on policy. The risk associated with 4.4 and 55 pound vehicles was assessed. In addition, the impact that the choice of different TLS would have on the requirements for major metrics such as UAS failure rate, link reliability, population density and airspace density allowed was examined. This phase is important to begin the dialogue regarding what is an appropriate safety target for UAS operations. While this thesis will not recommend a particular TLS for use in the UAS integration process, it will demonstrate the effect of choosing a TLS on the requirements for UAS system reliability.

For the purpose of this thesis, the concern is only with setting a TLS that serves as the border between unacceptable and tolerable risk. Movement further down the spectrum within the tolerable region requires tradeoffs involving cost that were beyond the scope of this effort. However, it is important to note that the steps in Phase 3 will help provide benefit data that could be used, in conjunction with cost data, to conduct the tradeoffs necessary in any decision-making process.

When discussing an appropriate TLS it is also important to introduce the concept of background risk. This is the risk that is already posed by daily life from a variety of activities and is generally acceptable by society. This background risk concept is used by the nuclear power industry as a way to baseline and approach any additional risk posed by a nuclear power plant. Federal safety regulations for nuclear power use overall risk in the vicinity of a power plant and the sum of all cancer risks as metrics with which to create their safety goals [77]. Listed in Table 34 and Table 35 below are several examples of background risk from both transportation and non-transportation related activities.

Table 34: General Background Risk Values

Information	Value	Units	Source	Citation
Fatalities due to Air Transport	3.45×10^{-6}	Annual Probability	Range Commanders Council	[197]
Fatalities due to Firearms	2.30×10^{-6}			
Fatalities due to Falls	1.61×10^{-5}			
Fatalities due to Accidents in the Home	1.02×10^{-4}			
Casualties due to Weather Events (U.S.)	9.64×10^{-6}			
Casualty Risk of Construction Workers	4.21×10^{-2}			
Worker Fatality Rate	0.018	Fatalities per Million Work Hours	Bureau of Labor Statistics	[211]

What is interesting about the general values in Table 34 is that very mundane activities such as falls or simply accidents in the home actually carry a fairly high probability of being a fatality, compared to air transportation. However, studies show that people perceive risk and are thus willing to accept risk differently depending on several factors that include their level of control over the risk, their willing participation in the risk, whether the risk is natural or man-made as well as how the risk is portrayed in the media [212].

Therefore, the risk due to hazards in the home are more accepted because people have a sense of control over them and home deaths are not typically newsworthy. On the other hand, people are typically less tolerant of fatalities due to air travel because they feel they have no control over the risk and the risk of death becomes exaggerated due to the associated news coverage. Keeping these concepts in mind, any deaths due to UAS activity are certain to be newsworthy, heightening the sense of perceived risk. Society will feel they have little to no control over UAS flights other than living in an area with less UAS activity, and most of society will not voluntarily take part in UAS activity. All of these factors point toward a lower tolerance of risk and a higher corresponding safety threshold.

An interesting comparison can also be made by examining safety statistics for other transportation-related activities. In Table 35 are statistics for air and road traffic. These statistics provide metrics to help determine what is already an acceptable level of safety since society has not decided to eliminate these activities but merely insists that safety improvements are made when they are practicable.

Table 35: Transportation-Specific Background Risk Values

Information	Value	Units	Source	Citation
Nationwide Statistics (1984-2004) for all Air Accidents	1.09×10^{-5}	Accidents Resulting in Fatality per FH	NTSB	[176]
Nationwide Statistics (1984-2004) for all Air Accidents	1.48×10^{-7}	Accidents Resulting in Ground Fatality per FH	NTSB	[176]
Nationwide Statistics (1984-2004) for Midair Collisions	8.08×10^{-7}	Fatality Rate Onboard Aircraft per FH	NTSB	[176]
Nationwide Statistics (1984-2004) for Midair Collisions	2.22×10^{-8}	Fatality Rate on Ground per FH	NTSB	[176]
Nationwide Statistics (1984-2004) for General Aviation Accidents	8.4×10^{-8}	Fatality Rate on Ground per FH	NTSB	[176]
Nationwide Statistics (1984-2004) for Air Taxi and Commuter Accidents	9.97×10^{-8}	Fatality Rate on Ground per FH	NTSB	[176]
Nationwide Statistics (1984-2004) for Transport Accidents	3.13×10^{-8}	Fatality Rate on Ground per FH	NTSB	[176]
Nationwide Statistics (1984-2004) for all Accidents	7.6×10^{-8}	Fatality Rate on Ground per FH	NTSB	[176]
Derived Statistics for all non-Midair related Accidents	5.58×10^{-8}	Fatality Rate on Ground per FH	Derived from NTSB Statistics	N/A
Nationwide Traffic Statistics for 2009	1.14×10^{-8}	Fatality Rate per Mile	NHTSA	[213]
Nationwide Traffic Statistics for 2009	1.58×10^{-5}	Non-motorist Fatalities per Capita	NHTSA	[213]

Four of the statistics in Table 35 above stand out. The first is the fatality rate on board aircraft due to midair collisions. This is a measure of the current risk level to participants in air travel due to midair collisions. The second is the fatality rate on the ground or for third-party individuals per flight hour due to midair collisions and gives a sense of the bystander casualty rate. The third is the fatality rate for all accidents for third-party persons per flight hour. From this value one can deduce the bystander casualty rate for all accidents not caused by midair collisions which would be roughly 5.58×10^{-8} fatalities per flight hour, the fourth statistic highlighted above.

As with any new endeavor of this magnitude and importance, setting the right level of safety is crucial. There will be some optimal level of safety that ensures the shortest time required to achieve a level of integration that is required by the law and by the desire of stakeholders. If the TLS is set too conservatively, UAS will likely require significant improvements in reliability or risk mitigation measures, or be more restricted in their operations. Conversely, safety levels that are set too low could actually result in a series of early mishaps; perhaps high profile casualties, that lead to a public outcry over UAS integration and set the effort back. The balance required in setting TLS values has been recognized in previous studies [98]. A theoretical comparison of the amount of time it takes to reach full UAS integration into the NAS compared to how conservative the safety levels are set appears in Figure 68. The optimal TLS is a level that is not overly conservative but does not also risk setbacks due to a perceived lack of safety on the part of UAS.

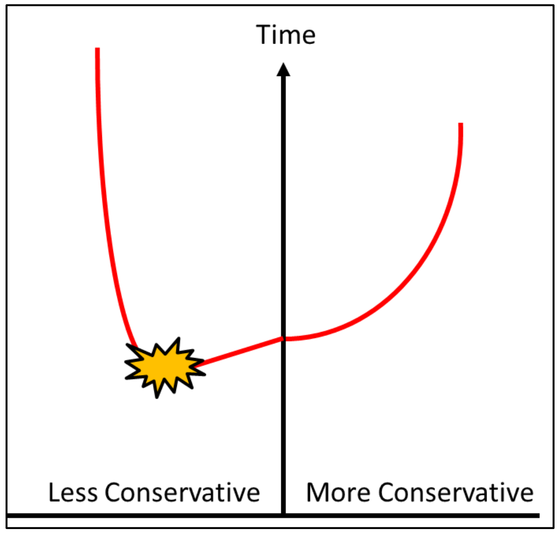


Figure 68: Optimal TLS Concept

The four TLS values that will be examined in more detail appear below in Table 36 . These four values were chosen for two reasons. One, as a whole, they represent a fairly wide range of TLS values from the very stringent Transport Category requirements to the much less stringent Single Engine requirements of the FAA. These TLS values also represent significant comparable values for manned aircraft or background risk. When necessary, the values were converted to the fatality per flight hour metric in use throughout this research. For example, TLS #1 actually refers to catastrophic failures of the Transport Category aircraft. Similarly, TLS #2 refers to work hours but was converted to flight hours for the purpose of this thesis.

Table 36: Example Target Levels of Failure / Safety

#	Information	Value	Units	Source	Citation
1	Commuter / Transport Category Aircraft Requirements	1×10^{-9}	Failures per FH	FAA / EASA / SAE	[35, 73, 74]
2	Worker Fatality Rate	1.8×10^{-8}	Fatalities per Work-Hour	Bureau of Labor Statistics	[211]
3	Single, Recipricating Engine, Less Than 6000 lbs, Non-Transport Acft Requirements / Risk Criteria for UAS Operations	1×10^{-6}	Failures / Fatalities per FH	FAA / Range Commander's Council	[38, 72]
4	Fatality Rate for all Aviation from 1990-2009	2.56×10^{-5}	Fatalities per FH	NTSB Database	[178]

Part 2a. Determine the Level of Safety of two Near-Term Requirements

In this section, two near-term integration requirements were examined using the models developed in Part 1. The two types of vehicles chosen were based on the 2012 FAA Modernization bill that mandated earlier integration dates for 4.4 and 55 pound vehicles. The purpose of this sub-part was to demonstrate the implication of the models to predict risk levels and determine what level of safety these two types of UAS could achieve based on current UAS characteristics.

To reiterate, the three main areas being compared in this portion of the research all pertain to the ground risk model. The model was completed using three different methods to compute ground casualties. In the first method, the impact area is solely based on the dimensions of the air vehicle and the population density is assumed to be uniform on the ground. In the second method, the impact area is based on previous studies of aircraft crashes and the population is assumed to be spread between residential, open, and commercial areas as well as vehicles based on the NHAPS study. In the final method, the protection effects that shelter offers are added to the previous model.

Case Study 1: 4.4 Pound Vehicle

The FAA law passed in February, 2012 mandated that the FAA enter into agreements with government agencies to allow for the use of 4.4 pound air vehicles for public safety purposes, presumably law enforcement, under certain provisions. The vehicles had to operate within line of sight of the operator, below 400 feet, during daylight and in Class G airspace [12]. To better understand the risk posed by these small air vehicles, that weight category was used in the different models described above. It is important to note that at this phase of the research, no risk mitigation measures were included in the model. For example, the UAS employed no SAA measures, there was no logic to avoid crashed in built up areas, and the vehicle architecture did not allow for autonomous operations to mitigate the risk of a lost link scenario.

The first comparison made with the 4.4 pound vehicle scenario utilized an average population density of 3,800 people per square mile, a value representative of a densely populated area comparable to Orange County, California [147]. Using the simple model, the behavioral pattern model and the behavioral pattern model with shelter effects with a simulation with 50,000 iterations, the estimated casualty results appear in Figure 69. The unit of measurement is estimated casualties per 10 million flight hours. This is a different metric than the typical unit per flight hour or per 100,000 FH simply to provide values that are more easily understood. The values are for predicted ground casualties per 10 million FH and are compared to bystander casualty statistics for GA aircraft during a 20 year period between 1984 and 2004.

Several important results emerge from this effort. First, the simplified model significantly exceeds the casualty estimates from the other models. This is because the geometric method of predicting impact area, over-predicts for small air vehicles and there is no shelter factor. Further, because of the urban setting and small size of the vehicle, the shelter effects reduce casualty estimates to approximately 33% of the estimate obtained from using behavior patterns alone. The last two columns show the results from the full ground risk model and historical data. What is significant about these values is that for a very small air vehicle, in an urban setting, the model indicates that the UAS would be twice as deadly as manned aircraft have been to people on the ground overall.

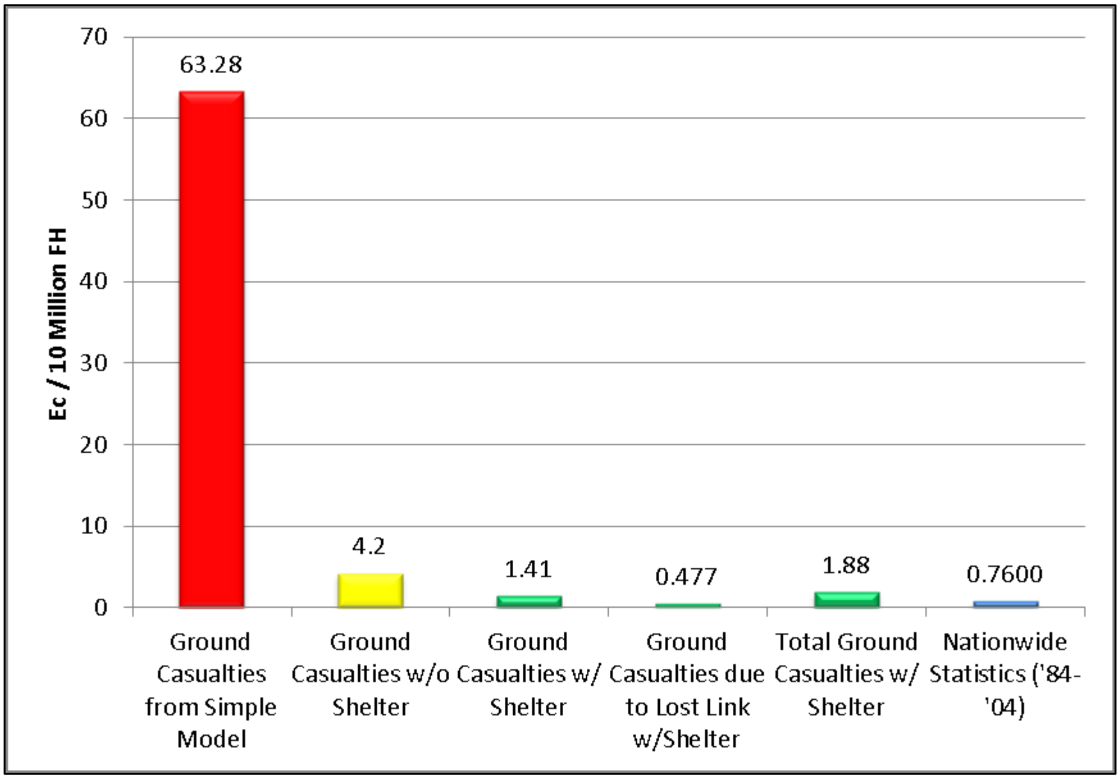


Figure 69: Ground Casualty Estimates in an Urban Environment (4.4 lb Vehicle)

The results above examine the impact of using the various models in an urban environment, but one of the objectives of this part was to determine the risk that a 4.4 pound vehicle poses to the overall country. To analyze these results, the terminal effects model was analyzed using the continuous population density distribution for the country.

In the first instance, using the ground risk model and the population distribution function, the estimated overall casualty rate for the 4.4 pound vehicle had a mean value of 0.0641 per 10 Million FH compared to the nationwide GA statistics of 0.76 per 10 Million FH. These values represent an order of magnitude difference and demonstrate that the 4.4 pound air vehicle with no risk mitigation measures in place would pose far less risk to people on the ground if operated in areas with population density representative of the United States. A means test below confirms that the mean of the simulation results is significantly different than the historical data for manned aviation bystander fatalities. The p-value for the t-test conducted is less than 0.0001, thus voiding the null hypothesis that the means are the same.

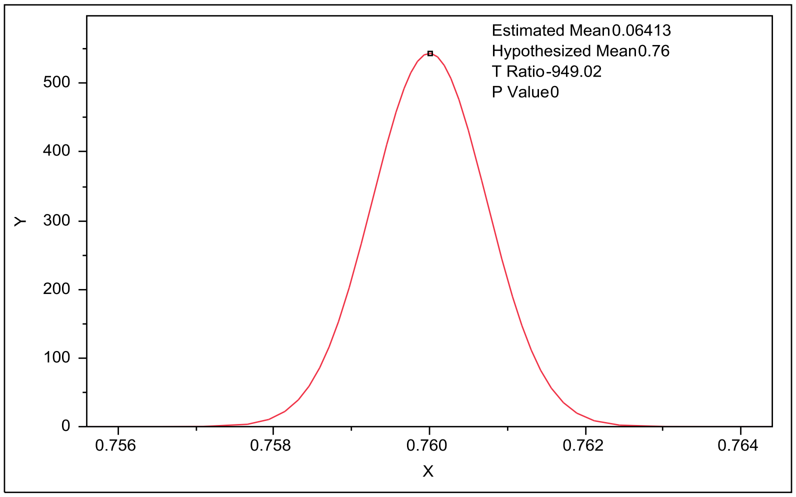


Figure 70: Means test for 4.4 Lb Vehicle Ground Casualty Rate

To determine the value for population density that makes operations of the 4.4 lb vehicle too dangerous, the scatterplot in Figure 71 was used. Each dot on the scatterplot represents a case from a Monte Carlo simulation conducted using the ground risk model. This figure shows the data in terms of ground deaths per 10 Million FH compared to a uniform distribution of the overall population density. Using the data plot, a line on the vertical axis is included at 0.76 Deaths per 10 Million FH to correspond to a theoretical limit derived from the GA historical data. The assumption here for this case is that the UAS should be no more dangerous to people on the ground than GA aircraft were for the period in question. To be extremely conservative and ensure no cases exceed this value, one can add the line on the horizontal axis which limits the data to those cases which occur at less than 760 people per square mile. Everything to the left of that vertical line will cause fewer deaths per FH for a 4.4 pound UAS than GA aircraft, using the full terminal effects model, no mitigation factors and current representative UAS reliability values.

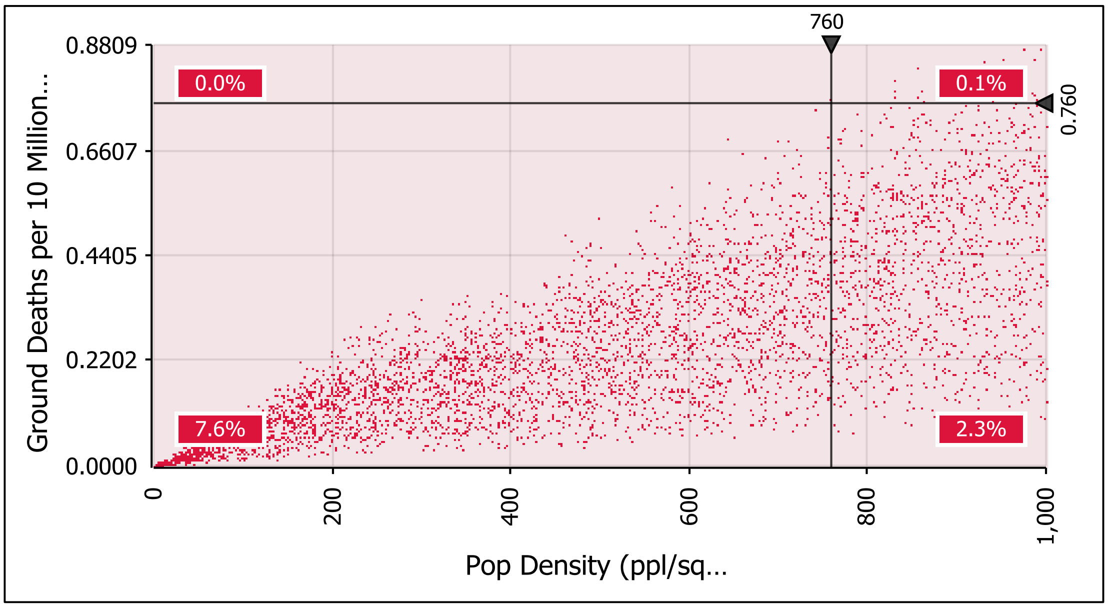


Figure 71: Scatterplot for 4.4 Lb Case

The significance of these values lies in the following data. From the U.S. Census data by county, there are 3,143 counties in the country. Of these, 2,967 have a population density lower than 760 people per square mile and these counties account for over 97% of the land mass of the country. This means that with no mitigation measures in place, an air vehicle weighing 4.4 pounds, with current reliability levels, could operate over 97% of the country or all but 176 counties and still pose less risk to bystanders than GA aircraft have. A summary of the results described above for the 4.4 lb air vehicle simulations with no risk mitigation measures in place appears in Table 37.

Table 37: Summary of 4.4 Lb Unmitigated Ground Risk Simulation

Variable	Value	Units
Target Third-Party Fatality Rate	0.760	Fatalities / 10 Million FH
Population Density Required for 100% Confidence in Not Exceeding Target	760	People / mile^2
Number of Counties Nationwide	3,143	#
Number of Counties with fewer than 760 People / mile^2	2,967	
Counties with fewer than 760 People / mile^2	94.4	%
U.S. Land Mass with fewer than 760 People / mile^2	97.7	
Number of People Living in Areas with greater than 760 People / mile^2	129 Million	#

The final important statistic to note from Table 37 above is in the last row. Although almost 98% of the land mass of the United States would be safe to fly over for a 4.4 lb vehicle, over 129 million people live in the roughly 2% of the land mass deemed unsafe. As a result, risk mitigation would be required before being allowed to operate over the 2% of the land mass in built-up areas. The implementation of risk mitigation analysis will be discussed in Part 3.

Case Study 2: 55 Pound Vehicle

The 55 pound case study was also examined because this weight was specifically mentioned in the 2012 FAA law. Although the law for 55 lb vehicles actually describes model aircraft, it is still useful to see how the case applies to the UAS models in this research. Using the 3,800 people / square mile case for the urban scenario and a 55 pound air vehicle, the results for the simulations appear in Figure 72. These results reveal several factors. First, the difference between the simple model and the full ground risk model is not as significant as it was in the 4.4 lb case. While the difference still represents over 20 deaths per 10,000,000 FH the two values are more comparable. The data also reveals that the effects of shelter are not as much of a consideration in terms of preventing penetration of buildings. While this seems counterintuitive, the kinetic energy of a 55 lb air vehicle is typically about 13,500 ft-lbf and that value does not include thechemical energy of the fuel. Based on the studies on material absorption from Table 11, only 14” RC has the ability to withstand that type of force. That type of material is typically reserved for hardened structures.

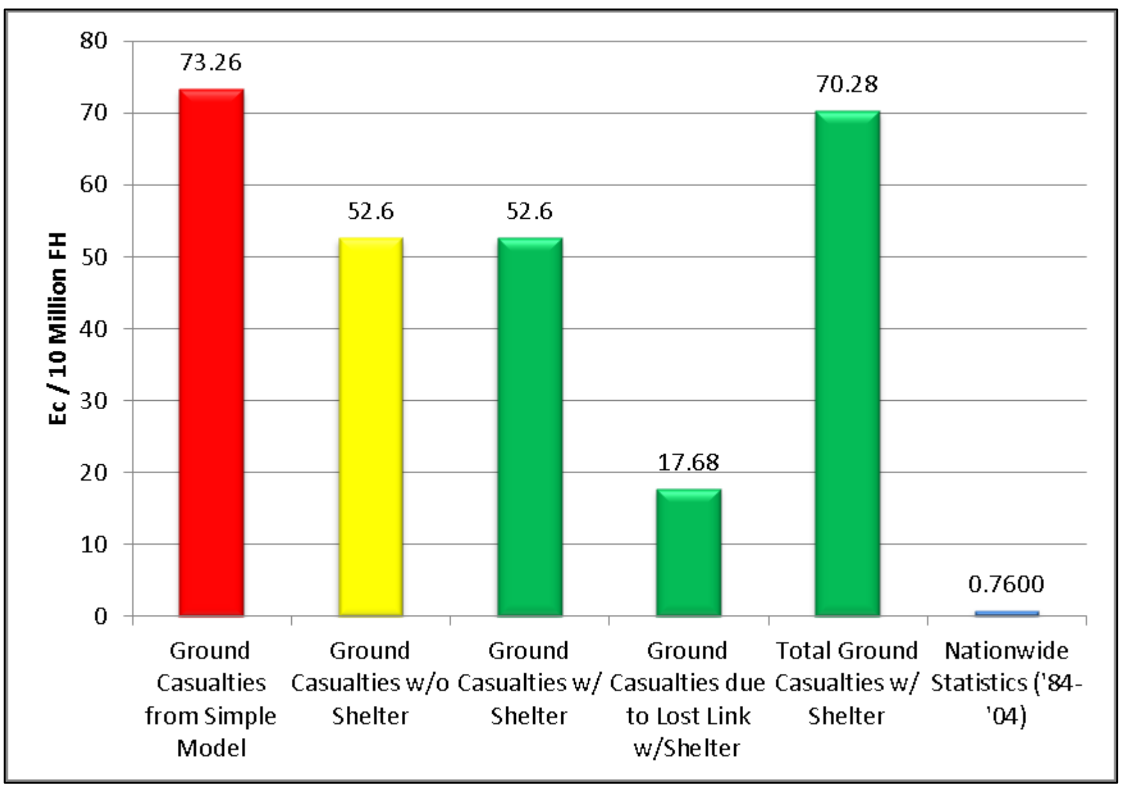


Figure 72: Ground Casualty Estimates in Urban Environment (55 lb Vehicle)

When the same experiment using the distribution for population density across the entire country is conducted, the ground casualty rate for the 55 pound vehicle is approximately 2.41 fatalities per 10 million FH. This value exceeds the manned historical rate of 0.76. Again, a test of the means indicates that the value of 0.76 is outside the range allowable to accept the null hypothesis that the mean value from the simulation and the historical value are the same.

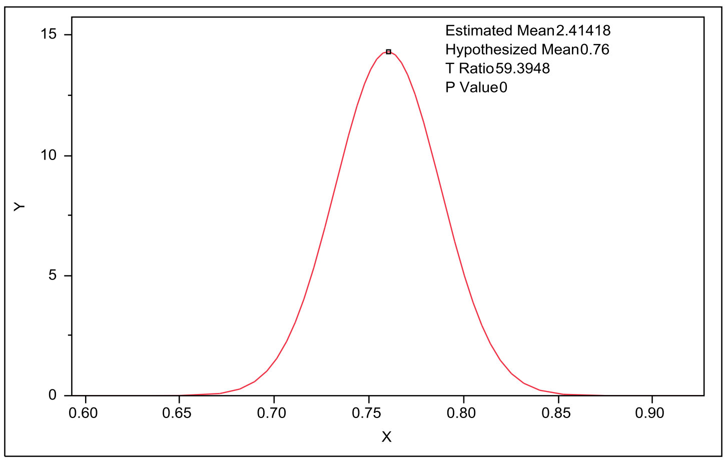


Figure 73: Means Test for 55 Lb Vehicle Ground Casualty Rate

The simulation demonstrates that a larger vehicle would require significant mitigation measures to close the risk gap to the level of GA aircraft, if that were the goal. To demonstrate the population density required to be 100% certain that the third-party death rate would not exceed GA statistics, the scatterplot in Figure 74 is used. In this case, the number of cases that would pose less risk than GA aircraft are significantly less. The requirement is to be below 19 people per square mile. However, this criterion applies to 847 counties in the U.S. and approximately 55% of the land mass of the country. However, almost 300 Million people, or roughly 97% of the country's population lives in the 45% of the land mass with population density values greater than 19 people per square mile. A summary of these results appears below in Table 38.

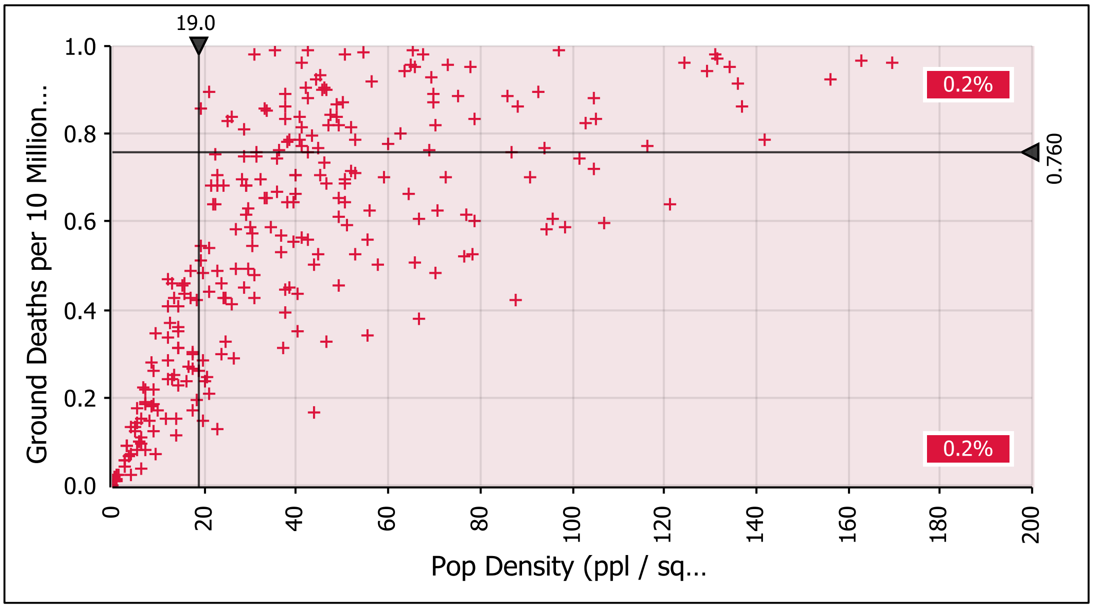


Figure 74: Scatterplot for 55 Lb Case

Table 38: Summary of 55 Lb Unmitigated Ground Risk Simulation

Variable	Value	Units
Target Third-Party Fatality Rate	0.760	Fatalities / 10 Million FH
Population Density Required for 100% Confidence in Not Exceeding Target	19	People / mile^2
Number of Counties Nationwide	3,143	#
Number of Counties with fewer than 19 People / mile^2	847	#
% of Counties with fewer than 19 People / mile^2	26.9	%
U.S. Land Mass with fewer than 19 People / mile^2	55.4	%
Number of People Living in Areas with greater than 19 People / mile^2	299 Million	#

Part 2.b. Determine the Impact of Applying Manned Reliability Levels on UAS

Without a framework to translate reliability into safety, it is tempting for administrators to leverage existing manned aircraft failure rate requirements and apply them to UAS operations. If this is the case, one could argue that UAS would initially be held to the highest standards since they are a new technology and any initial catastrophes could cause public backlash and set integration efforts back. If one makes this assumption, the logical requirement would be to hold UAS to the same failure rate standards as Transport aircraft, or no more than 1 $x10^{-9}$ catastrophic failures per FH. The alternative on the other end of the spectrum would be to use the failure rates required for small, single-engine aircraft or 1 $x10^{-6}$ catastrophic failures per FH. To examine the implications of either choice, two experiments were conducted.

First, the ground casualty prediction model was executed with a range of UAS sizes and weights, based on the data derived from current UAS models. These parameters originally appeared in Table 7. The experiment was also repeated specifically for a 4.4 lb UAS. In both cases, the system and link failure rates were set at 1×10^{-9} and 1×10^{-6} failures per hour. The continuous distribution for the population density that represents the United States was used as well to gain a better understanding of national level safety values expected from the model. A review of two historical fatality rates appears in Table 39 for comparison. These rates represent the total fatality rate for all types of aviation in the first category, and the fatality rate for only bystanders caused by GA aircraft over two different 20 year periods. The results of both simulations appear below in Table 40 and Table 41.

Table 39: Review of Pertinent Historical Fatality Rates

Information	Fatalities per FH	Source	Citation
Aviation Fatalities due to all Aviation Operations ('90-'09)	2.56×10^{-5}	NTSB Database	[178]
Ground Fatalities Caused by General Aviation Accidents ('84-'04)	8.40×10^{-8}	NTSB Data from Clothier Paper	[176]

Table 40: General UAS Held to Specified Failure Rates

Information	Fatality Rates (per FH) at Specified Failure Rates		Source	Citation
	1×10^{-9}	1×10^{-6}		
Ground Casualties	4.53×10^{-12}	4.53×10^{-9}	Simulation	N/A
Ground Casualties due to Lost Link	2.17×10^{-12}	2.17×10^{-9}		
Total Ground Casualties	6.7×10^{-12}	6.7×10^{-9}		

A graphic depiction of the results from Table 40 appears in Figure 75. This figure shows the two historical fatality rates of interest above and the fatality rates obtained from the model set to the two failure rates below. To the right of the data boxes are numbers that indicate the orders of magnitude that separate the values in question connected by the brackets.

Using a range of UAS weights representative of current air vehicles, the difference between predicted casualty rates and the historical bystander casualty rates are anywhere between one and four orders of magnitude, depending on the failure rates used. UAS held to Transport Category failure rate standards would be seven orders of magnitude safer than the overall aviation fatality rate.

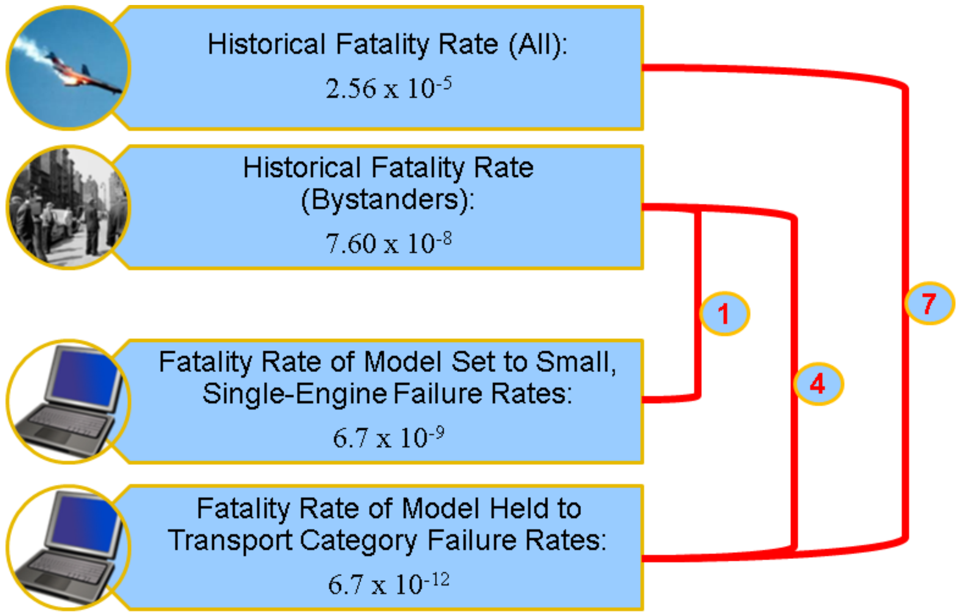


Figure 75: General UAS Held to Specified Failure Rates

The results of the same type of analysis performed using only a 4.4 lb air vehicle appears in Table 41 and graphically in Figure 76. What is extremely clear from the results is that requiring small UAS such as these to maintain very stringent reliability standards puts them on a trajectory to exceed manned aviation safety records by many orders of magnitude.

Table 41: 4.4 lb Air Vehicle Held to Specified Failure Rates

Information	**Fatality Rates (per FH) at Specified Failure Rates**		**Source**	**Citation**
	1×10^{-9}	**1×10^{-6}**		
Ground Casualties	3.85×10^{-15}	3.85×10^{-12}	Simulation	N/A
Ground Casualties due to Lost Link	7.84×10^{-16}	7.84×10^{-13}		
Total Ground Casualties	4.63×10^{-15}	4.63×10^{-12}		

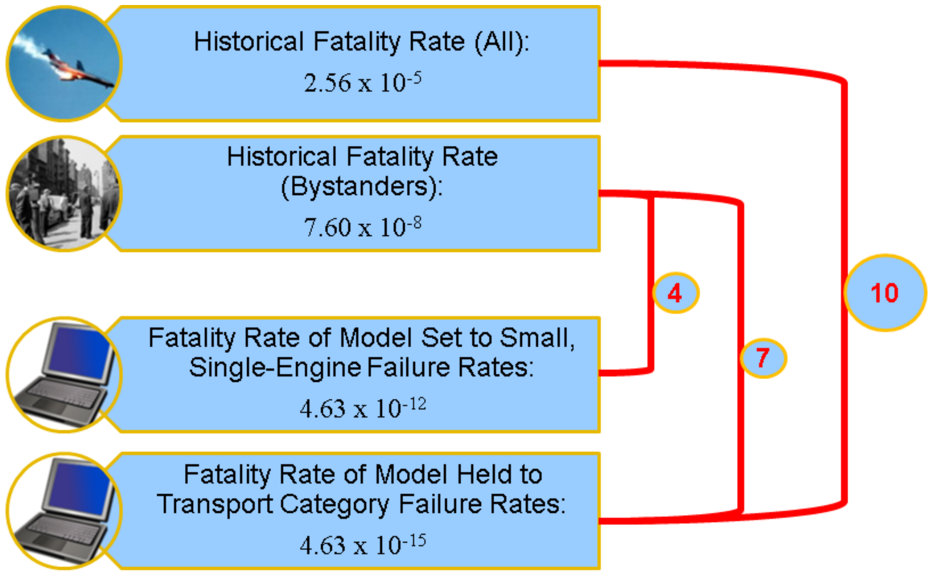


Figure 76: 4.4 Lb UAS Held to Specified Failure Rates

The differences between the UAS predicted casualties and the GA third-party casualties and casualties for all aviation are seven and ten orders of magnitude. As expected, this gap is reduced by three orders of magnitude when the reliability requirements are instead set to the less stringent standards set for small, single engine aircraft.

The demonstration of difference in safety levels for UAS also becomes a cost issue. Depending on the source, current UAS failure rates are somewhere on the order of magnitude between $1x10^{-2}$ to $1x10^{-4}$ per FH. Even if one uses an optimistic approach and uses the latter value, an improvement to $1x10^{-6}$ is two orders of magnitude difference. First, there is the question if reliability improvements of that magnitude are possible. Second, there are the cost considerations required for such improvement.

An LMI study comparing reliability improvements for defense projects developed a model to estimate the cost of reliability improvements. The model they developed uses a ratio of reliability improvement and a factor to account for the average production cost of the unit to account for the scale of the project [214]. Using their model, the investment required to shift from MTBF values of 10,000 hours to 1,000,000 hours is a factor of over 142,000 multiplied by the average production cost of the system. This is clearly not a viable option for a system that is supposed to reduce costs. Moreover, it is unnecessary in many cases given the fact that reliability levels that high for UAS produce safety levels well beyond what manned aircraft achieve.

Table 42: Risk Comparison

Information	Fatalities per FH	Source	Citation
Fatality Rate for 4.4 lb UAS with $1x10^{-6}$ Failure Rate	4.63×10^{-12}	Model	N/A
Bystander Fatality Rate for GA Aviation	8.40×10^{-8}	NTSB Data from Clothier Paper	[176]
Total Fatality Rate for Aviation	2.56×10^{-5}	NTSB Database	[178]

This argument is important because manned aircraft already use weight as a metric to determine reliability standards. For example, AC 23.1309, which is the source for the Single Engine reliability requirement above in Table 36, uses 6,000 lbs as a dividing line for different reliability standards [72]. Based on this fact and the evidence from the simulations above in Table 41, there is a compelling argument for creating additional certification categories that take the potentially low weights of small UAS into account.

The difference between the predicted UAS fatality rate of 4.63×10^{-12}, and the overall aviation fatality statistic of 2.56×10^{-5} fatalities per FH is even greater. In addition to the advantage of size, these values reflect the advantage of being unmanned. While GA aircraft are twice as likely to have an accident as an air taxi aircraft [215], the fact is that some of the accidents contributing to the 2.56×10^{-5} casualty value must have been aircraft held to a higher reliability standard than GA. Yet the casualty rate for these aircraft is 7 orders of magnitude greater than the predicted UAS value. This is likely because of both the increased size of some of the manned accidents in question as well as the increase in passengers on board. Unmanned aircraft do not suffer from both penalties as their size increases.

Part 2.c. Determine the Impact of Choosing Different TLS

The purpose of this subpart was to demonstrate the impact of choosing various TLS on the level of integration possible, based on current UAS characteristics and reliability levels. To do this, the model was run using typical weights, sizes, and failure rates for UAS and utilizing typical values for airspace and population density to simulate the operational environment. After 5000 cases were run, the results were filtered to determine how many cases met TLS levels at different orders of magnitude ranging from 1×10^{-9} to 1×10^{-5}. These values were chosen to reflect the risk range outlined in Table 36. The results of the experiment appear in Figure 77 and Figure 78. At the most stringent levels, less than one percent of all cases would meet the specified TLS. As the TLS is eased by an order of magnitude at a time, the number of general cases that meets the TLS increases exponentially until at the 10^{-5} level, over 80% of all likely scenarios meet the TLS. It is important to keep in mind that current manned aircraft safety achieves a casualty rate on the order of magnitude of 10^{-5}.

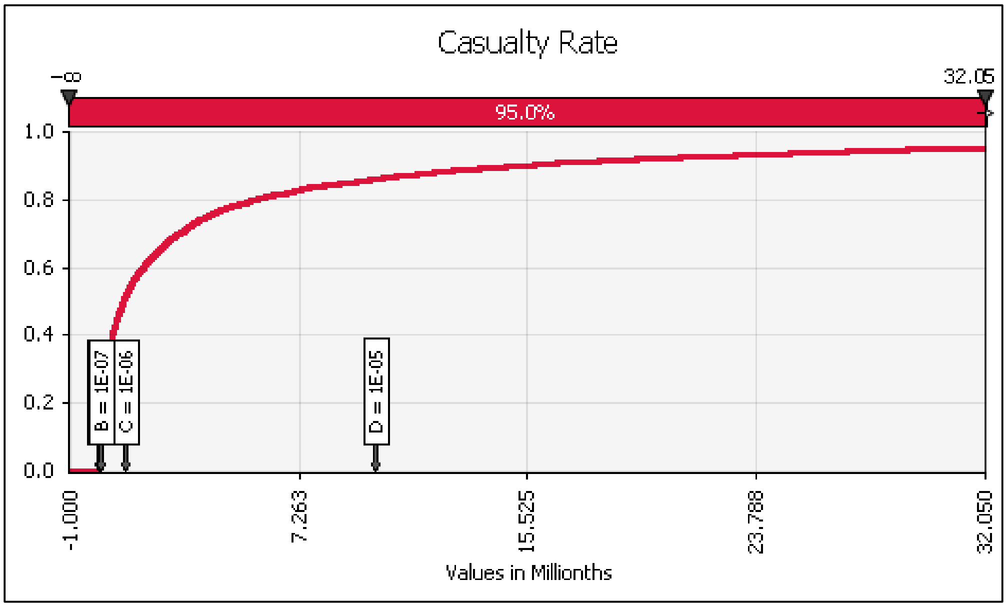


Figure 77: Casualty Rate CDF for General Cases

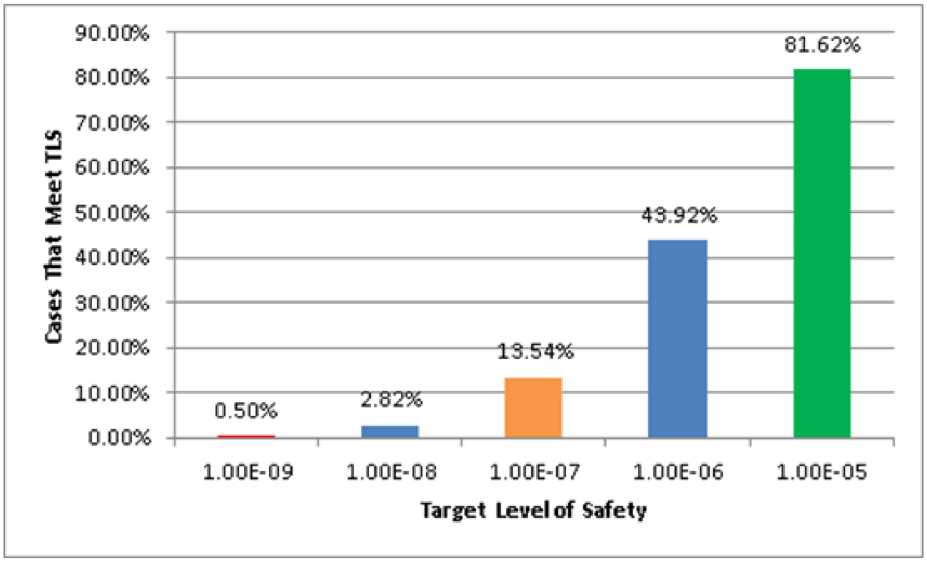


Figure 78: Summary of Cases that Meet Specified TLS

This data has tremendous implications for decision makers setting TLS values. When attempting to set the appropriate TLS value, there could be a tendency to determine what is appropriate for society and then set the value one order of magnitude safer to be conservative. However, that decision could potentially eliminate large portion of the various combination of UAS weights and operating environments allowable or increase reliability requirements significantly.

It is illuminating to put the TLS values above into perspective. While it may be tempting to avoid setting the current manned fatality rates as a TLS in an attempt to be safer, a comparison to fatality rates for something as benign as being in one’s own home reveals a stark contrast. In Table 44 are several statistics and also a few theoretical calculations to provide a comparison of the theoretical risk due to UAS operating under TLS #4 and the risk associated with being in the home.

To make the comparisons similar, several calculations were necessary. First, a survey of GA aircraft was used to determine the number of hours flown per GA airframe per year. An assumption was used that the number would be double for UAS. This assumption was based on the lower operations cost of UAS, the potentially longer endurance times and the fact that multiple operators could rotate shifts on one UAS compared to the shorter duty days of pilots on manned aircraft. All of the data used to predict the annual casualties caused by UAS under TLS #4 and the number of fatalities in the home appears in Table 43.

Table 43: Data Used to Predict UAS Casualties and Home Fatalities

<table>
<tr><th>Information</th><th>Value</th><th>Units</th><th>Source</th><th>Citation</th></tr>
<tr><td>Number of GA Aircraft in 2009</td><td>223,877</td><td rowspan="5">#</td><td rowspan="2">GAMA Databook</td><td rowspan="2">[198]</td></tr>
<tr><td>Number of GA Hours Flown in 2009</td><td>23,763,000</td></tr>
<tr><td>GA Hours per Airframe</td><td>106.14</td><td>Calculated</td><td>N/A</td></tr>
<tr><td>Number of UAS Predicted by 2019</td><td>20,000</td><td>JPDO</td><td>[10]</td></tr>
<tr><td>Theoretical UAS Hours Projected Based on 2 x GA Hours per Airframe and UAS Airframes</td><td>4,245,724</td><td>Calculated</td><td>N/A</td></tr>
<tr><td>Fatality Rate for all Aviation from 1990-2009</td><td>2.56×10^{-5}</td><td>Fatality per FH</td><td>NTSB Database</td><td>[178]</td></tr>
<tr><td>Fatalities due to Accidents in the Home</td><td>1.02×10^{-4}</td><td>Annual Probability</td><td>Range Commanders Council</td><td>[197]</td></tr>
<tr><td>U.S. Population in 2010</td><td>308 Million</td><td>#</td><td>Census Data</td><td>[147]</td></tr>
</table>

The key value in Table 44 is the last one which shows that with the annual flight hours predicted for UAS in the short term and with fatality rates held to TLS #4, the total annual expected deaths from UAS operations would be just over 100. This compares to over 50,000 for the flu and pneumonia, over 30,000 due to accidents in the home, over 5,000 just for being a pedestrian and over 600 due to General Aviation operations. Clearly, the magnitude of the risk to the public, or the societal risk would still remain extremely low even when choosing a TLS that on first appearances seems risky and lower than manned aircraft reliability standards by an order of magnitude.

Table 44: Risk Comparison Data

Information	Fatalities per Year	Source	Citation
U.S. Deaths due to Influenza and Pneumonia in 2009	53,692	Centers for Disease Control	[216]
Suicides in 2009	36,909		
Home Accidents per Year Based on Probability and Population	31,416	Calculations	N/A
Deaths due to Motor Vehicle Accidents in 2009	26,216	Centers for Disease Control	[216]
Unintentional Pedestrian Deaths in 2009	5,219		[217]
Workers Killed on the Job in 2010	4,609	OSHA Website	[218]
Average Fatalities for General Aviation	631	AOPA	[175]
Projected Fatalities from UAS Based on Theoretical Hours and Manned Aviation Fatality Rates	108	Calculations	N/A

In the final steps of this process, the risk model is used to gain further insights into the nature of safety and UAS integration. The remainder of this section discusses those insights and implications for Part 3 of the research. For example, in Figure 79, a scatterplot matrix featuring some of the more important input variables related to the ground casualty rate is featured. The data is filtered so that the green points indicate data points that were equal to or less than the GA casualty rate discussed in the previous paragraph.

The trends from this graph show that the most critical factors ensuring safety remain the combination of weight and population density. Whereas there are data points that are safer than the TLS across a range of values for the other input variables, the box on the upper left indicates a limited combination of UAS weights and population density variables that will meet the theoretical safety level set for this analysis.

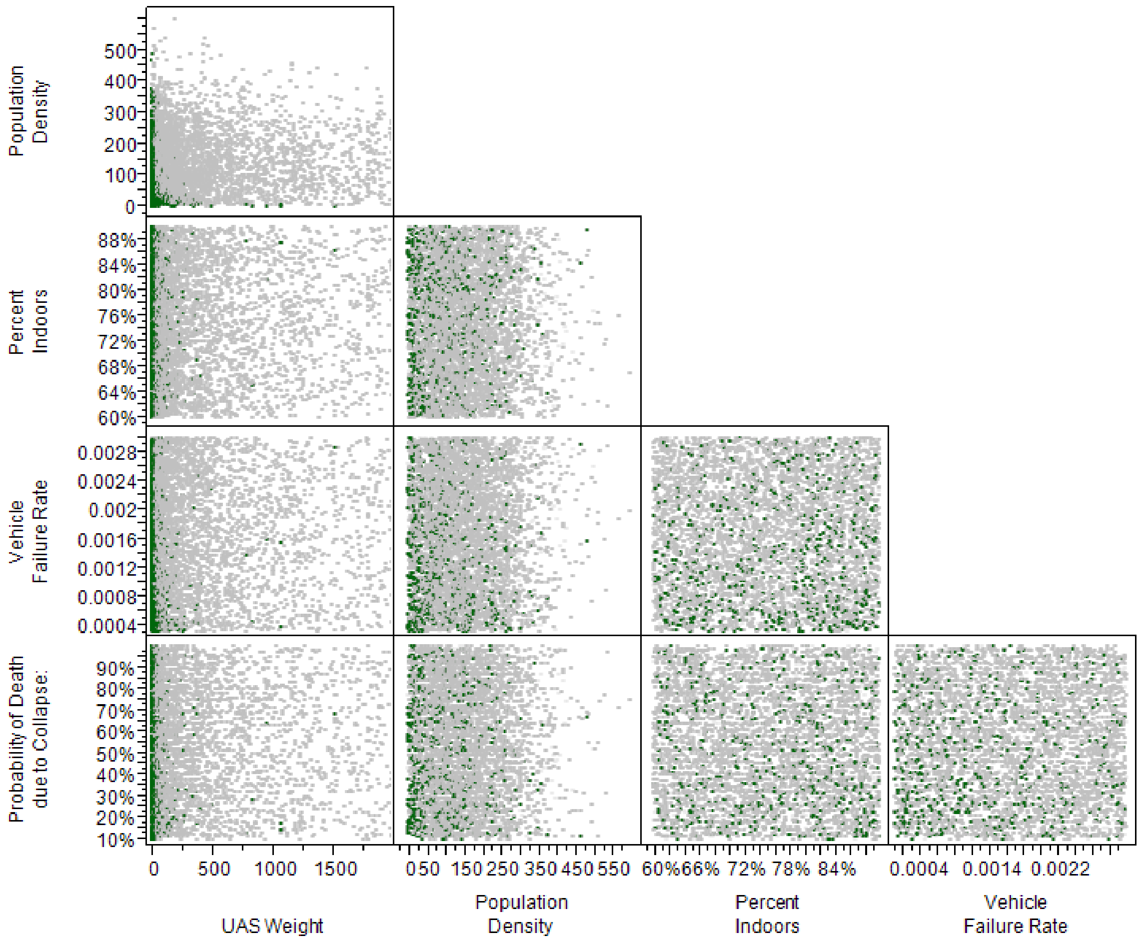


Figure 79: Scatterplot Matrix Filtered by Ground Casualty Rate

An even more interesting result appears in Figure 80, which features a surface profiler of the ground casualty response plotted against the UAS weight and population density variables. The interesting thing about this plot is that the trend indicates a slight, initial decrease in casualty rates as population density increases beyond a certain point. This is because of the data used to populate the model. As the population density increases, more people are indoors and the open area percentage decreases. As a result, more people are under shelter in an urban environment than in a rural one.

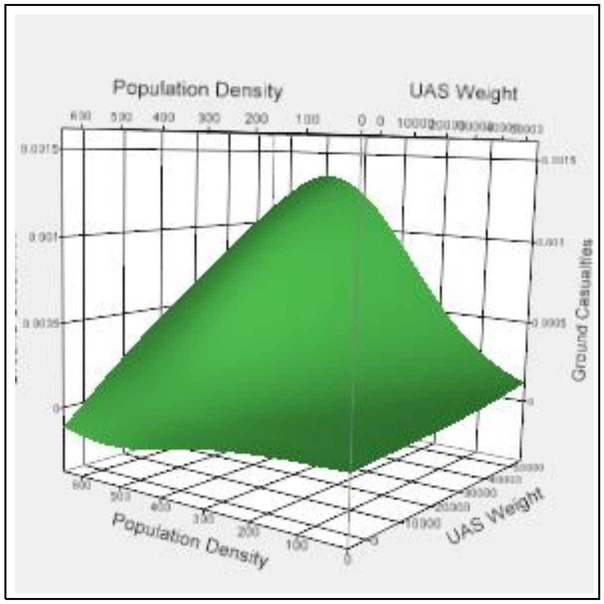


Figure 80: Ground Casualties vs. UAS Weight and Population Density

Next, for demonstration purposes, the author chose three values for air vehicle weights to show how the TLS value would affect each case. The breakdown for the weights were 4.4 lbs representing the small UAS in the 2012 FAA law, 500 lbs representing a larger vehicle perhaps representing a longer endurance urban law enforcement vehicle, and 5000 lbs representing a fairly large, sophisticated vehicle slightly larger than a typical Predator. In addition, the data from the sensitivity analysis from Part 1 was also analyzed to demonstrate the impact of imposing the General Aviation ground casualty rate (8.4 x 10^{-8} casualties per FH) on the full range of UAS cases.

The results of the first simulation conducted, analyzing a 4.4 pound vehicle, appear below in Figure 81. This figure is a Cumulative Distribution Function (CDF) for the total deaths per FH values over 10,000 cases run. Vertical marks based on TLS # 2 and #3 from Table 36 are featured as well as a comparison TLS value of 1 x 10^{-7} for reference. TLS values #1 and #4 are not shown because they would have appeared at the extreme left and right of the figure, respectively.

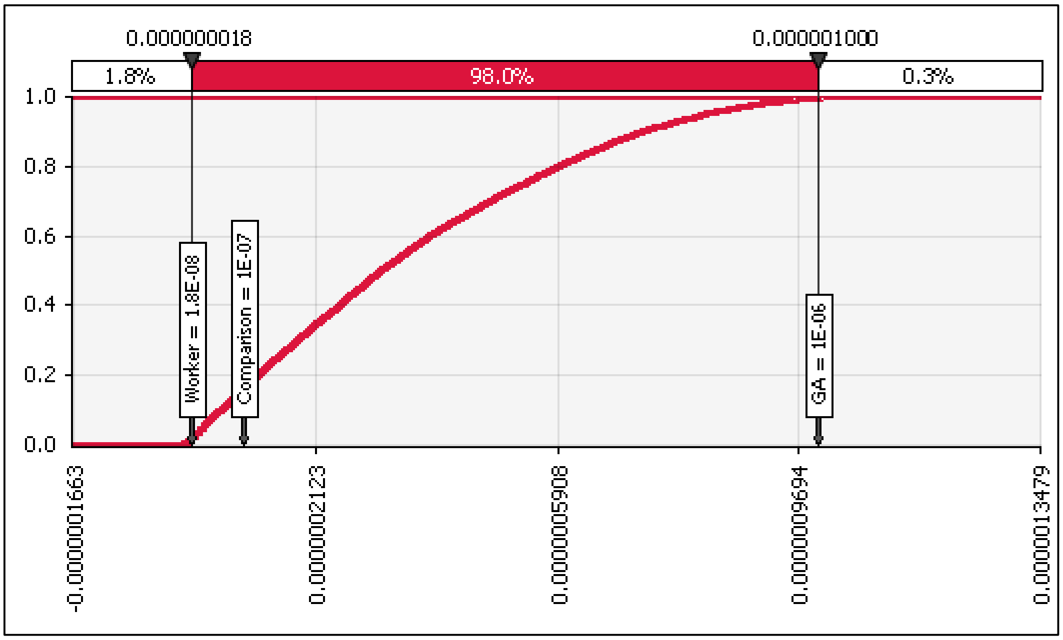


Figure 81: CDF for Total Deaths per FH for 4.4 Lb UAS

Examining Figure 81 reveals that the selection of a TLS creates very stark differences in the number of cases that would be allowable under those circumstances. For example, if the worker fatality rate of 1.8 x 10^{-8} deaths per hour is used as the target TLS, only 1.8% of the 4.4 lb simulation cases would have been lower than that value or acceptable. On the other hand, using the small aircraft reliability standard of 1 x 10^{-6} as a TLS, which is the acceptable TLS for UAS in the Range Commander's Council documents, only 0.3% of the simulation cases would be excluded. Using a value in the middle of 1 x 10^{-7} yields just over 20% acceptable cases. The value for TLS # 4, or historical fatality rates for manned aviation, would allow 100% of the cases to be acceptable.

Another way to use the data generated from this technique is to be able to conduct tradeoffs on safety decisions and the impact they have on reliability parameters. For example, using the 4.4 Lb vehicle in an urban environment again with a population density of 3,800 people per square mile yields the scatterplot below for the ground casualty rate compared to the vehicle failure rate. Using the results from the simulation one can obtain a relationship between the casualty rate and failure rates of the vehicle, in this case a linear one. In this particular case, the change in failure rate with respect to the change in casualty rate is approximately 12,000. This information can be used to determine the impact in a proposed change in a safety rate. For an example, see Equation 11 below. In this case, a proposed change in TLS from $1x10^{-6}$ to $1x10^{-7}$ requires a shift in reliability of 0.01 or one failure every 100 hours.

$$\Delta_{Failure\ Rate} = (1x10^{-6} - 1x10^{-7}) * 12000 \cong 0.01$$

Equation 11

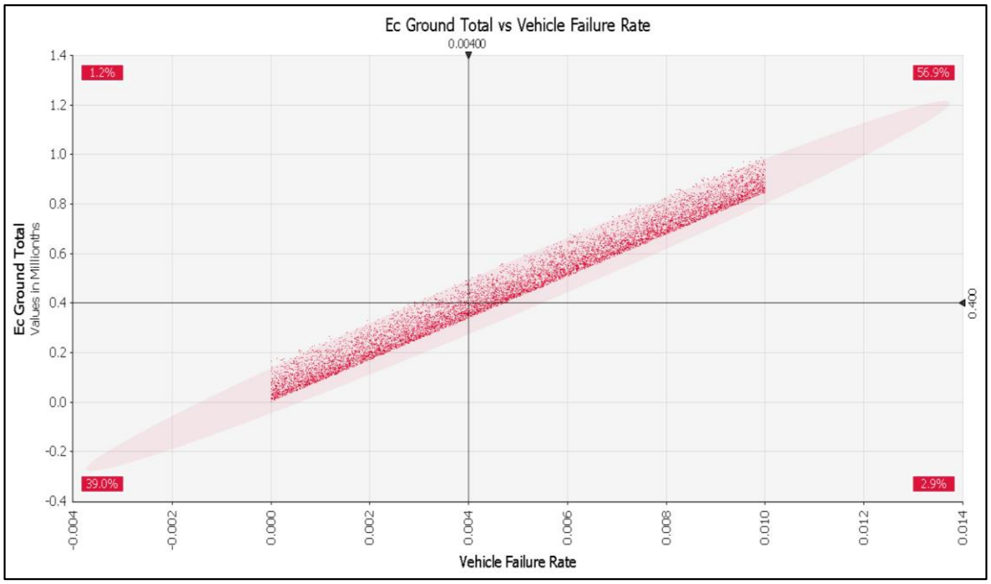


Figure 82: Scatterplot for 4.4 Lb Vehicle in Urban Environment

For a 500 lb air vehicle the same type of procedure was conducted. This time the results showed a higher degree of risk due to the increased size of the vehicle. The CDF, which appears in Figure 83 shows that if the Worker Fatality rate is used as a TLS, none of the unmitigated cases for the 500 Lb vehicle would be acceptable. At the GA rate for TLS #3 only 2.7% of the cases are acceptable. However, accepting historical manned fatality rates as a standard allows all of the cases to meet acceptability standards.

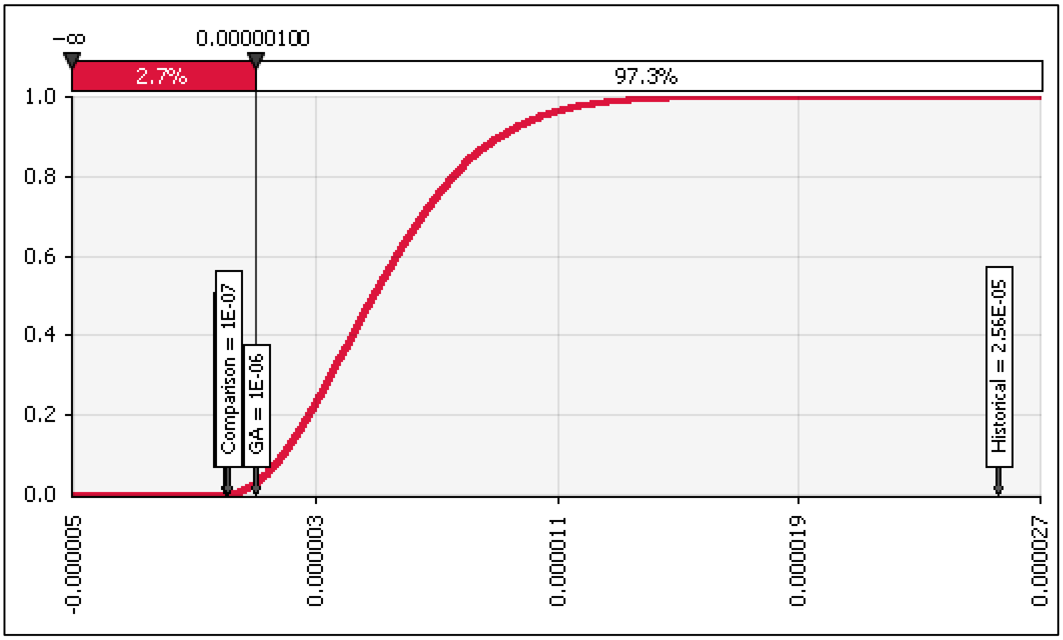


Figure 83: CDF for Total Deaths per FH for 500 Lb UAS

Finally, using a 5,000 Lb vehicle as a test case yields the results below in Figure 84. For a vehicle of this size only 1.9% of the cases even meet historical fatality rate acceptability standards, or TLS #4. Clearly mitigation would be required for vehicles of this size or larger before they could operate in environments representative of the overall NAS.

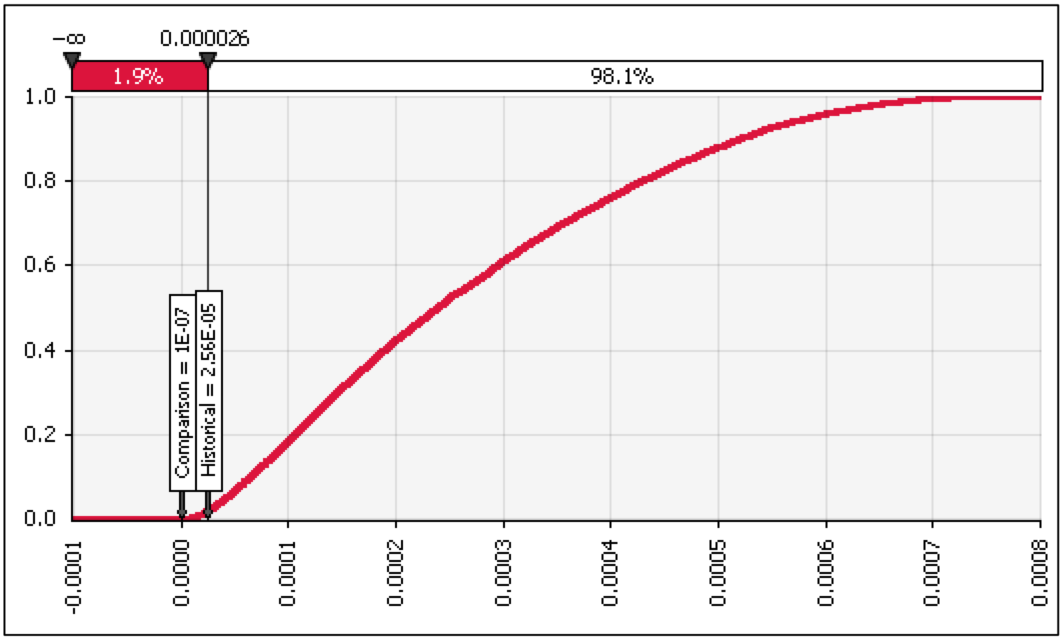


Figure 84: CDF for Total Deaths per FH for 5000 Lb UAS

Mitigating risk is an important topic for UAS integration and one that will be addressed in more detail in Phase 3. However, an examination of the contributing factors to risk can be accomplished using the tools inherent in the @Risk software to determine those input variables with the most serious impact on the total casualty rate. The contributions, in order of most to least important for the 5000 Lb vehicle example appear in Figure 85 and Figure 86. Both figures show mapped values for the regression coefficients. In other words, instead of showing how a change in one standard deviation of the input variable changes the output's deviation, the values displayed on the x-axis and in the bars in the tornado graphs are the actual change in output value based on a change in one standards deviation of the respective input variable [153].

For ground casualties, clearly the leading contributor to variability is the population density variable followed by the vehicle or system failure rate. Thus reducing the variability or decreasing the values of these two input variables would have the most effect on reducing ground casualties. This result is intuitive but the analysis does indicate that in the near-term, limiting the areas that UAS can fly over to lower population densities will actually have more impact on increasing safety than improving vehicle reliability.

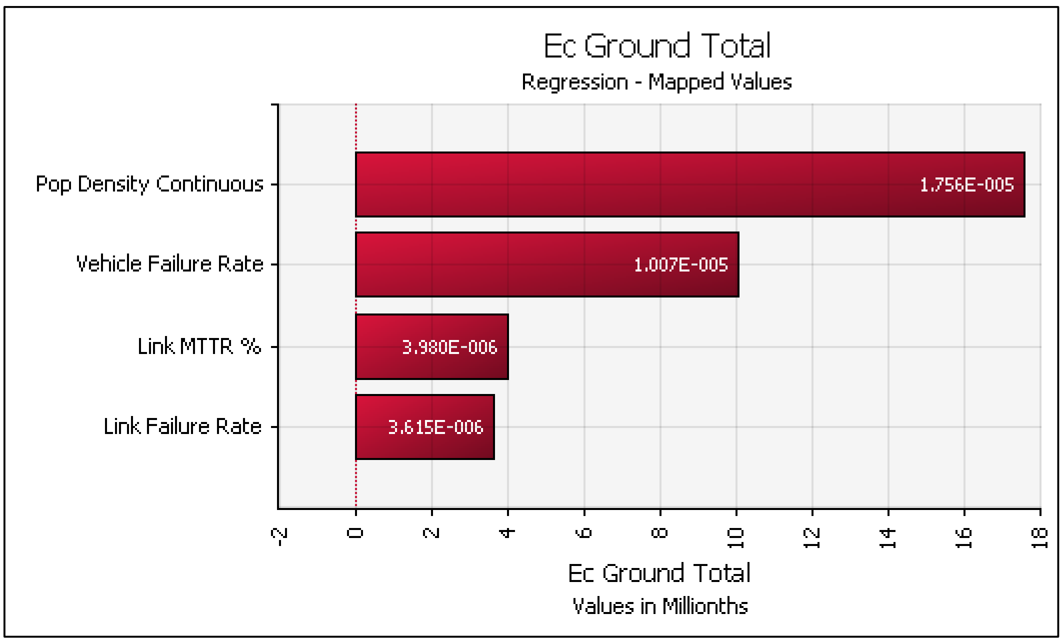


Figure 85: Tornado Graph for 5000 Lb UAS (Ground Casualties Only)

In Figure 86 are the mapped regression values for total casualties with casualties due to midair collisions included. In this case, the aircraft density value has a strong effect on total deaths. At this point in the modeling process, the UAS are considered to have no avoidance capability whatsoever so any near midair collision must be avoided by the manned aircraft. The architecture is also represented by operations in primarily uncontrolled airspace and the vehicles have no autonomy so a lost link condition places the air vehicle without any ability to avoid collisions. As a result, the air to air risk is very high until mitigation measures are put in place during Phase 3 of this research.

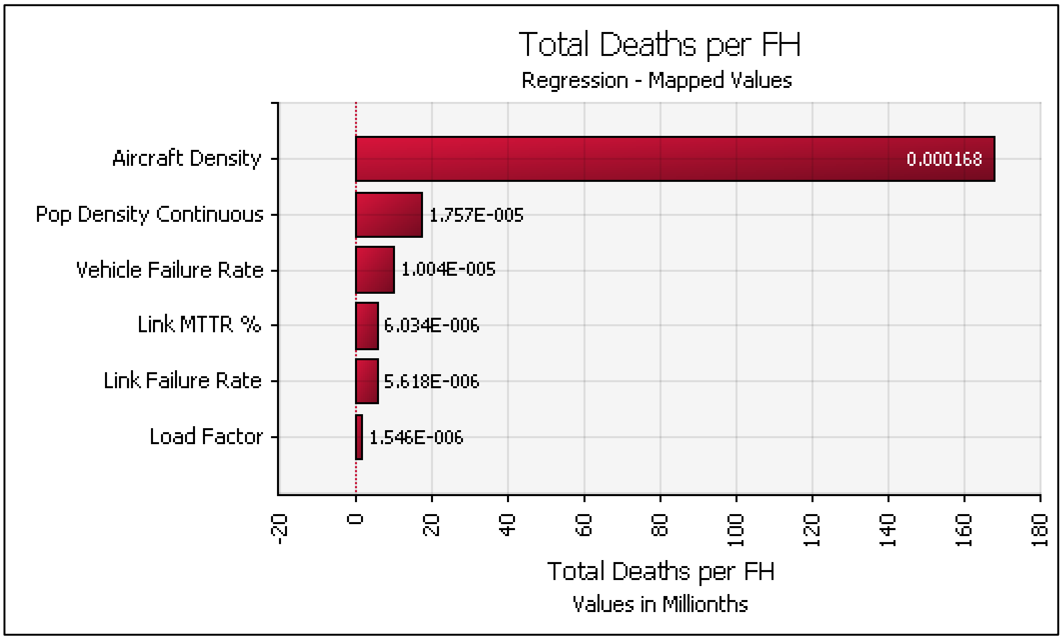


Figure 86: Tornado Graph for 5000 Lb UAS (Total Casualties)

The primary implications of this analysis is that any near-term integration concepts and certification standards will likely consist of combinations of air vehicle weights and operating environments, characterized by population density, allowable for UAS operations. As will be seen in the Conclusions section, these criteria are used to suggest standards for UAS certification and operations.

Part 3: Applications of the Framework

During the first two parts of this thesis, the focus has been on demonstrating the impact of adding the layers of realism to the ground and air risk event tree models as well as examining the implications of choosing various target levels of safety. The purpose of this third and final phase was to first demonstrate how the entire framework could be used by stakeholders to set safety goals and verify compliance with those goals. In addition, the concept of using these tools for decision-making is introduced. The decisions are related to both the reliability and operational environment of the UAS as well as any risk mitigation strategies employed. Up to this point in the research, mitigation has not been employed as a means to reduce the risk posed by UAS.

To fully demonstrate the framework, three operational scenarios are offered. The first scenario involves a larger UAS operating in a sparsely populated environment in a border patrol mission. The second scenario involves a medium-sized air vehicle operating in response to a disaster in the Midwestern United States. This scenario will involve low levels of other air traffic and a rural to suburban population density on the ground. The third and final scenario involves a smaller air vehicle operating in a law enforcement or surveillance capacity in the airspace above New York City. This scenario represents a very densely populated air and ground environment. The specifications for all three scenarios appear below in Table 45.

.

Table 45: Scenario Input Data Summary

Information		Value	Units	Source	Citation
Scenario 1: Border Patrol w/ Predator Class Air Vehicle	Vehicle Weight	10,500	Lbs	CBP Website	[219]
	Vehicle Reliability	2.0×10^{-4}	Fail / hr	DoD UAS Roadmap	[4]
	Link Reliability	4.3×10^{-4} to 5.05×10^{-3}	Fail / hr	MITRE and LMI Reports	[50, 138]
	Population Density	38.3	Ppl / mi^2	Census for Santa Cruz County, AZ	[147]
	Airspace Density	1×10^{-7} to 1×10^{-8}	Acft / nm^3	Based on Airspace Density Charts	[102]
Scenario 2: Suburban Disaster Response w/ Hunter Class Vehicle	Vehicle Weight	1950	Lbs	DoD UMS Roadmap	[137]
	Vehicle Reliability	2.4×10^{-4}	Fail / hr	DoD UAS Roadmap	[4]
	Link Reliability	4.3×10^{-4} to 5.05×10^{-3}	Fail / hr	MITRE and LMI Reports	[50, 138]
	Population Density	87.1	Ppl / mi^2	Census Average for Missouri	[147]
	Airspace Density	1×10^{-6}	Acft / nm^3	Based on Airspace Density Charts	[102]
Scenario 3: Urban Law Enforcement w/ Shadow Class Vehicle	Vehicle Weight	280	Lbs	UAV Roundup	[135]
	Vehicle Reliability	1.91×10^{-3}	Fail / hr	DoD UAS Roadmap	[4]
	Link Reliability	4.3×10^{-4} to 5.05×10^{-3}	Fail / hr	MITRE and LMI Reports	[50, 138]
	Population Density	27,012	Ppl / mi^2	Census for New York City Area, NY	[147]
	Airspace Density	1×10^{-3}	Acft / nm^3	Based on Airspace Density Charts	[102]

In addition to the data above, the three symbols in Figure 87 below depict where the three scenarios take place. The three locations represent a cross-section of population and airspace densities. The three UAS vehicles used in the scenarios also represent a representative cross-section of the types of air vehicles that are extremely common in military and law enforcement at the time this research was conducted and represent likely platforms for use in the various applications outlined in the three scenarios.

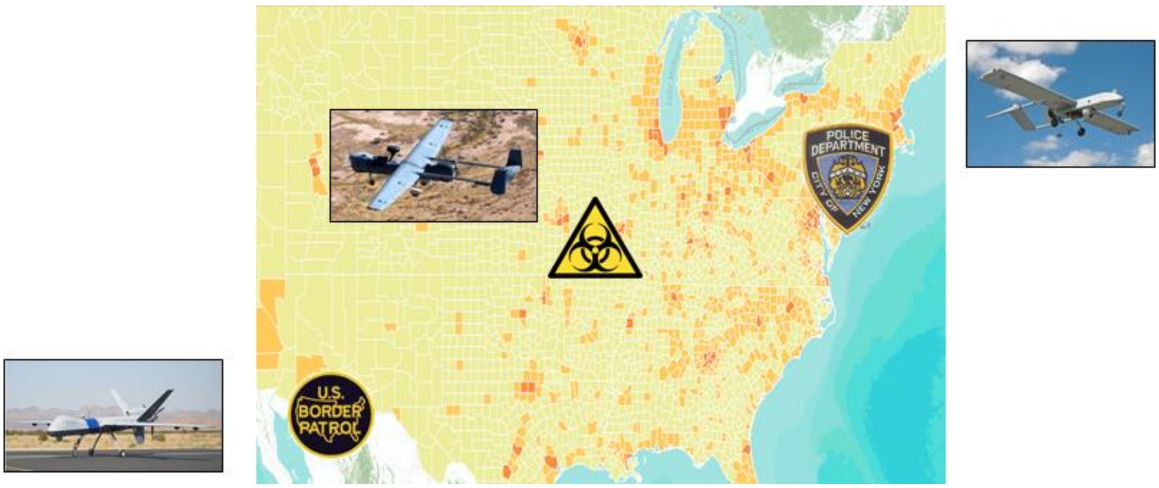


Figure 87: Phase 3 Scenario Locations

As a reminder from Figure 20, the purpose of this third and final phase is simply to demonstrate how the entire framework would be used within the larger decision and policy-making process. The four steps that will be detailed for each scenario is to Set the TLS, Assess the Safety of the Scenario with no mitigation and filter cases that do not meet the TLS to determine the largest sources of risk, and Evaluate mitigation measures, if necessary. Input to the decision-making process will also be discussed.

Scenario 1: Border Patrol Mission with 'Predator-Class' Air Vehicle

The U.S. Customs and Border Protection (CBP) agency already employs Predator Class B UAS for border surveillance along both U.S. borders and in the Southwest in particular. The air vehicles represented in this scenario are actually based from Libby Army Airfield in Sierra Vista, AZ. They provide a substantial amount of range, endurance, and payload capability [219]. While heavier than many of the vehicles analyzed so far, these UAS also tend to be more reliable than their smaller counterparts. In addition, this particular mission involves remote locations with very little air traffic or ground population.

For this first scenario, the mission would be considered routine. Patrolling the border would occur on a fairly regular basis and not necessarily in response to a major event or disaster. This information can help to determine the TLS for the scenario because it impacts society's risk tolerance. There is some precedent to setting the TLS one order of magnitude better than the current state of affairs or one order of magnitude more stringent for the general public than the mission essential personnel. For example, the Range Commander's Council figure, reprinted in Figure 88, shows that in almost every case the acceptable level of casualties or fatalities is one order of magnitude lower for the public than for mission essential personnel. Other than the UAS operators, it is reasonable to believe that everyone else on the ground is part of the general public, or third party. For manned aircraft, the current state is the value already discussed in

Table 36, or 2.56 x 10^{-5} fatalities per FH, so the TLS for this mission would be 2.56 x 10^{-6} fatalities per FH, or 25.6 per 10 million FH as the results will depict.

	TABLE 3-2. SUMMARY OF COMMONALITY CRITERIA			
	General Public		Mission Essential and Critical Operations Personnel	
	Max. Acceptable	Undesired Event	Max. Acceptable	Undesired Event
Per Mission	1E-6[b]	Individual Probability of Casualty	10E-6	Individual Probability of Casualty
	100E-6[b]	Expected Casualties	300E-6	Expected Casualties
	0.1E-6[a]	Individual Probability of Fatality	1E-6[a]	Individual Probability of Fatality
	30E-6[a]	Expected Fatalities	300E-6[a]	Expected Fatalities
	0.1E-6	Probability of Aircraft Impact	1E-6	Probability of Aircraft Impact
	10E-6	Probability of Ship Impact	100E-6	Probability of Ship Impact
	- - -	- - -	1E-6	Manned Spacecraft
Annual	3000E-6	Expected Casualties	30000E-6	Expected Casualties
	1000E-6[a]	Expected Fatalities	10000E-6[a]	Expected Fatalities

[a] Advisory Requirements.
[b] If a flight operation creates a toxic risk, then the range must separately ensure the allowable level of risk enforced by them does not exceed other standards for toxic exposure limits for the general public when appropriate mitigations are in place. Chapter 8 of the Supplement provides an approach for implementing this requirement.

Figure 88: Example of Casualty Criteria from Range Commander's Council [27]

Based on all of the input data described in Table 45, the initial safety assessment for scenario 1 appears below in Figure 89. The results depicted are the mean values of the results of the simulation conducted for the scenario, although the variance of the results was very minimal in this case because many of the key parameters such as the system reliability, vehicle weight, and population density were fixed. The results show that this particular scenario would not meet the TLS set based on one order of magnitude better than historical, manned fatality rates. The majority of the casualties are occurring due to a lost link condition, primarily because historical data for link failures occurs at a rate than can be up to an order of magnitude higher than the overall system failure rate. The casualties due to midair collisions are almost nonexistent due to the extremely low airspace density for this scenario along the remote border county in Arizona.

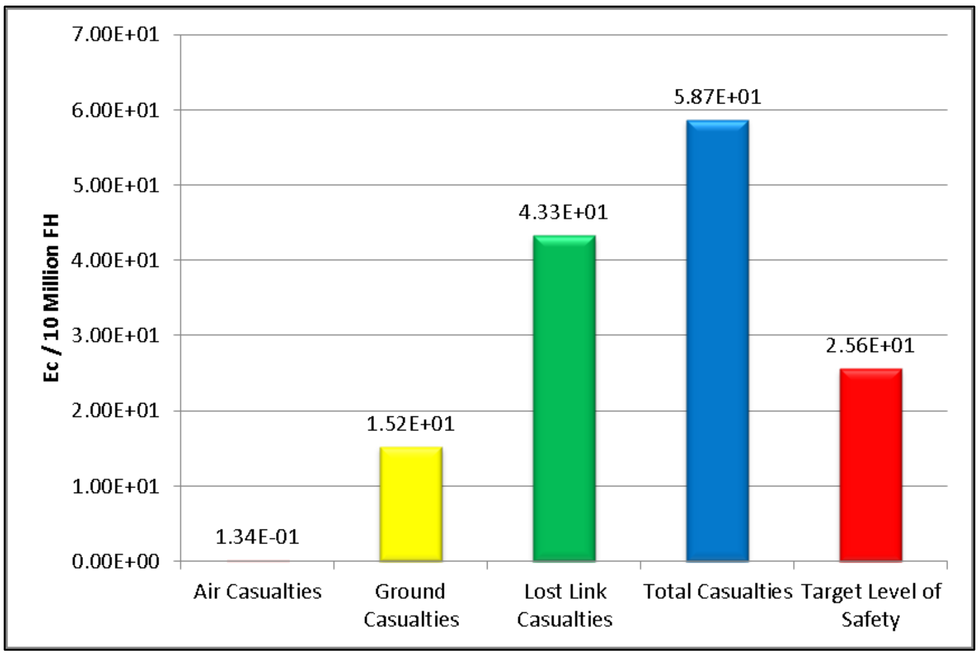


Figure 89: Initial Safety Assessment

To analyze this scenario in more detail or try to filter any cases that may be instructive, a scatterplot is created which appears in Figure 90. The figure shows that using the TLS set for this scenario, over 84% of the cases in the simulation are above the TLS, clearly an unacceptable condition. In addition, the situation is such that there is no clear way to filter the cases by the biggest contributor to the risk which is the link failure rate. The scatterplot shows that there is no link failure rate within the feasible input range set for this scenario that would meet the TLS with a level of certainty. As a result, the filtering, or lack thereof, for this scenario has led to the need for mitigation.

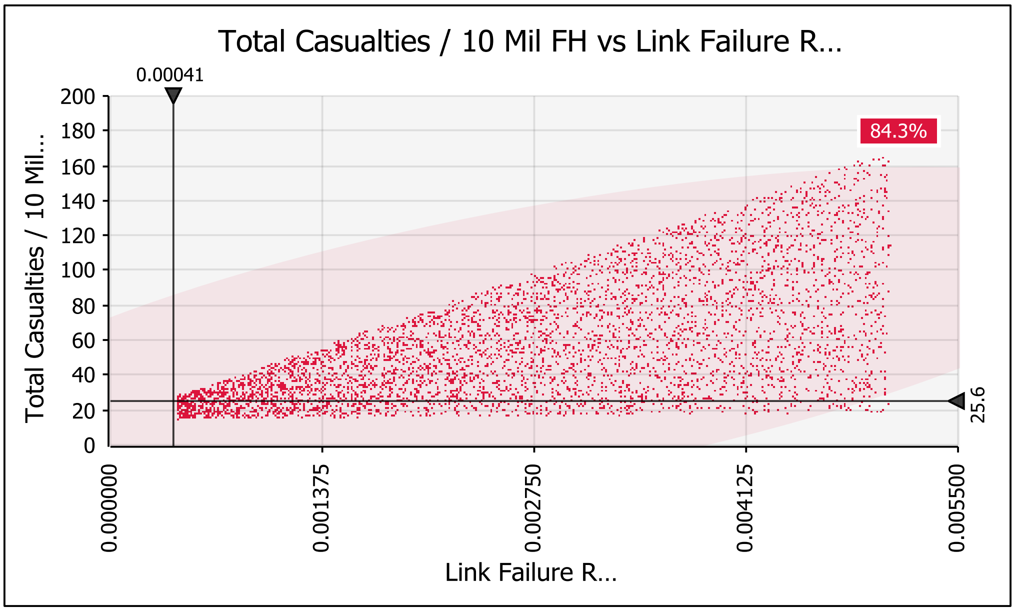


Figure 90: Total Casualties vs. Link Failure Rate (Unmitigated)

A further filter process that can be done is to actually filter out the cases where the scenario did not meet the TLS and examine the two major risk and variability drivers which are the link failure rate and an additional variable that varies the amount of time it takes to reestablish a link in the event of a link failure. The results of that process appear in Figure 91. The grey points are those that do not meet the required TLS. The green points represent points in the simulation that do meet the TLS. The x-axis is the actual link failure rate and the MTTR variable again is a percentage of the overall mission endurance that it would take to reestablish the link, in the event of a failure. For a review of that variable, see Figure 65 on page 205.

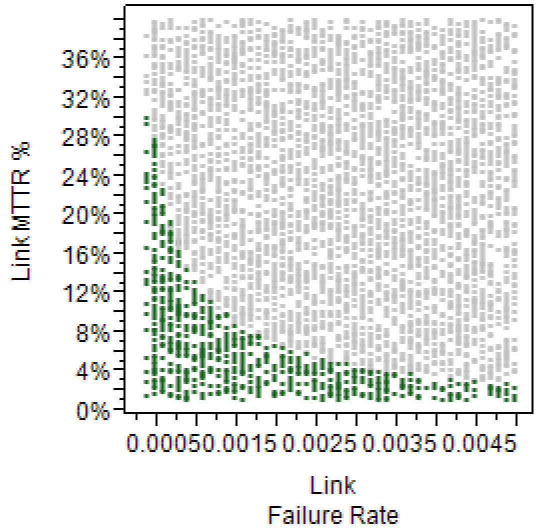


Figure 91: Filtered Monte Carlo Results for Lost Link Metrics

The information presented in Figure 91 represents a Pareto front [220] of solutions if one traces a curve where the green and gray points meet. The curve or front represents the worst combination of link failure rate and the mean time to reestablish link and still maintain safety values below the TLS. Any points above and to the right of the curve in the grey area represent infeasible solutions because they do not meet the TLS. Any green solutions below and to the left of the curve are feasible but would represent a higher level of reliability than is required to meet the TLS, therefore adding complexity and cost.

The decision maker would need additional information to help choose the best possible point to select based on other relevant factors. For example, if it is cheaper to make the link less likely to fail in the first place then it is to reestablish link quicker than one would choose a solution that moves to the left and up on the curve. In addition to gaining valuable information about potential solution spaces, the fact that the simulation demonstrated that the lost link condition is the highest cause of casualties for this scenario is valuable to guide stakeholders toward a solution. Clearly, this shortcoming must be addressed. If there is no way to make the link more reliable or quicker to reestablish, based on current technology, then a mitigation strategy must be employed.

One strategy currently employed by UAS operators is to pre-program a safe point into the UAS logic that the vehicle attempts to move toward in the event of a lost link. Of course, this requires some level of autonomy for the vehicle in the event it can no longer receive data from a ground-based operator. To demonstrate this mitigation strategy, the event tree is modified so that the UAS will move to an area that has a population density that is 10% of the current overall density and loiter. In the event link is not reestablished in time, the vehicle will still impact the ground, but do so in a less densely populated environment.

Adding the mitigation strategy to the simulation changes the results considerably. First, the mitigation strategy cannot be considered perfect. Therefore, an effectiveness value is placed into the simulation and varied uniformly between 0.5 and 0.99. This is a measure of whether the mitigation strategy of sending the air vehicle to a less densely populated area works or not. For example, the software that takes over in the event of a lost link could fail. Based on adding the mitigation measure, the updated results for the simulation appear below in the form of a cumulative distribution function in Figure 92. The figure shows how simply adding a mitigation measure to force the air vehicle into a less densely populated area in the event of a lost link raises the probability of achieving a casualty rate lower than the TLS to almost 80%.

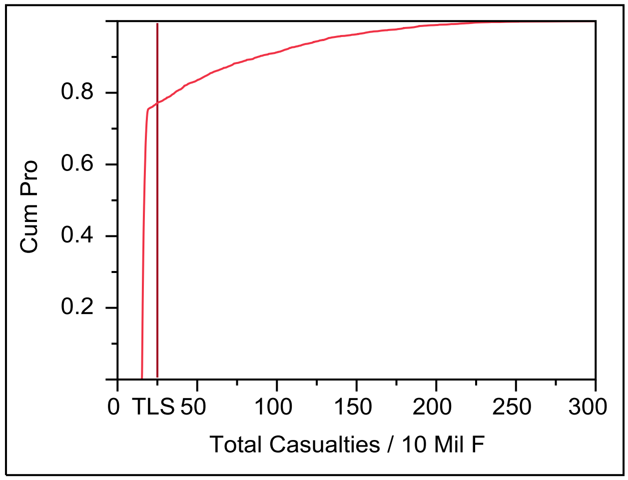


Figure 92: CDF with Safe Area Mitigation Measure in Place

The stakeholder now has several variables to optimize to include the link failure rate, the mean time to reestablish link, and the effectiveness rate of the safe area mitigation strategy. This last element is particularly useful if a designer plans to build the software and hardware requirements to implement this mitigation strategy. Using this method, a designer can set a minimum level of effectiveness for the mitigation system to achieve, in order to be considered capable of mitigating the risk to an acceptable level. The effectiveness level would be a combination of the reliability of the sub-system as well as its ability to actually performed the desired mitigating action; in this case guide the air vehicle to a pre-designated location or locations.

When a sensitivity analysis for the border patrol scenario is conducted, a few trends appear. First, for the ground casualties in Figure 93, when weight and population density are removed from the variability of the problem, the factor used to determine the impact area and the probability that a person inside a building becomes a fatality in the event of a penetration both become more important to the uncertainty in the response. In addition, the percentage of people indoors and even the chance of a fire occurring in the event of a crash now appear as regression coefficients. All of these factors point to the fact that there still needs to be additional research into the effects that a downed air vehicle has on people in sheltered areas and the impact area caused by a vehicle crash.

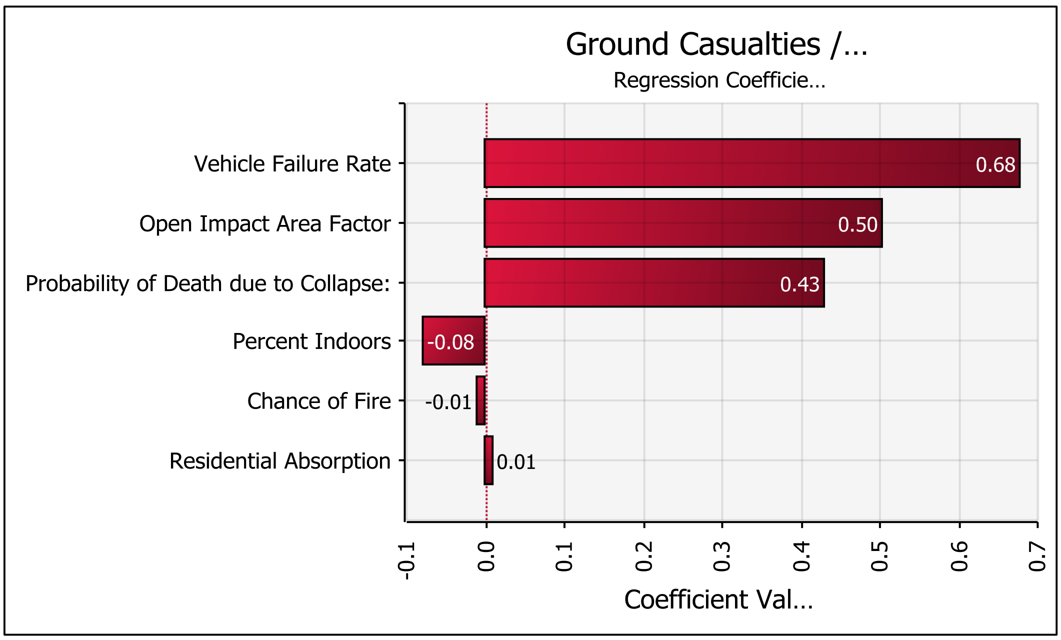


Figure 93: Sensitivity Analysis for Ground Casualties

The sensitivity analysis for air fatalities for this scenario appears in Figure 94. As can be expected, the primary factors that affect the variability of the response are all related to the degree to which the airspace is controlled and the level to which intruder aircraft and the UAS itself can avoid collisions. The vehicle speed becomes a minor factor since it relates to both the encounter rate, since a faster vehicle 'sweeps' out a larger volume of airspace and it also affects the degree to which avoidance can take place based on closure rates. The patterns for this sensitivity analysis were repeated for the next two scenarios so the analysis for air casualties in those two scenarios is not presented.

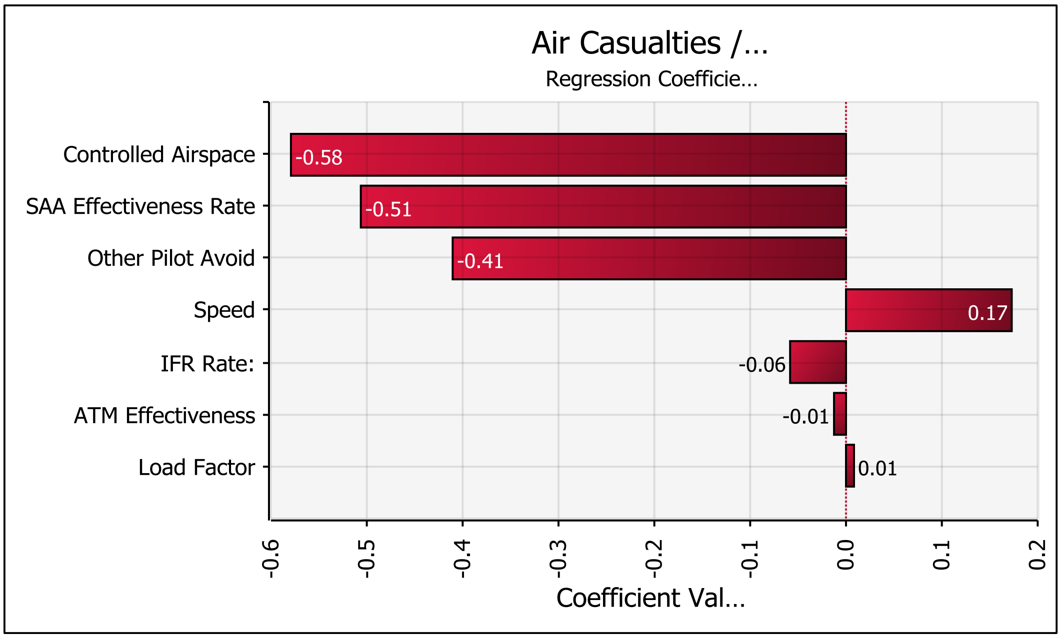


Figure 94: Sensitivity Analysis for Air Casualties

Scenario 2: Suburban Disaster Response with 'Hunter-Class' Air Vehicle

Not unlike the first scenario, UAS have already been in use for disaster response missions both in the U.S. and abroad. These missions range from mapping, survivor detection, and situational awareness of structures and facilities. UAS played roles in the aftermath of Hurricane Katrina in Louisiana in 2005 and the Haiti earthquake of 2010 [221, 222]. UAS offer a particularly attractive alternative when disasters create hazardous operating conditions for manned aircraft as in the aftermath of the Fukushima nuclear disaster in Japan [223].

This particular scenario represents a flooding disaster that could occur along the Missouri river and therefore represents a wider area mission than the law enforcement mission, which is confined to a smaller area or the border patrol scenario which is closely linked to a linear feature. However, unlike the other two scenarios, the disaster response mission also represents a situation that would not represent routine operations. As a result, the air traffic density was lowered to represent a restricted operating environment over the disaster area.

Consideration must be given to the status of this mission as a non-routine mission, when determining a TLS. The disaster response mission would be conducted when people are in need of information, supplies, or command and control in the disaster area. As a result, the harm of inaction must be weighed with the harm caused by operating UAS. Based on this analysis, for the purpose of this demonstration, the TLS for this mission was set at the same level of manned aircraft fatalities, as opposed to the previous scenario which was set one full order of magnitude safer than historical values. Based on the TLS and the data described in Table 45, the following results were obtained from the simulation.

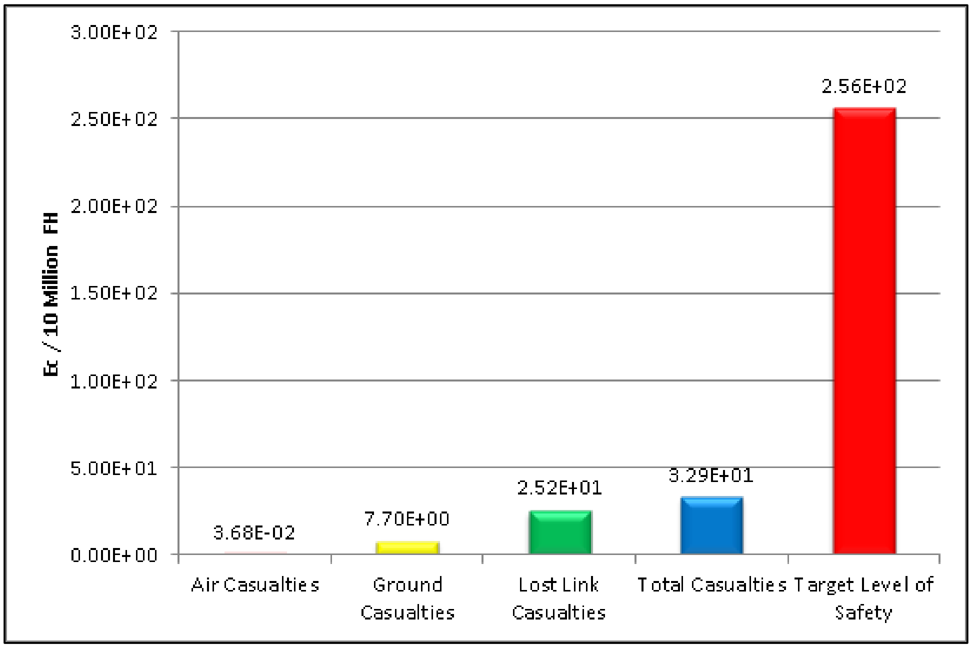


Figure 95: Initial Safety Assessment

As evidenced from Figure 95, the Hunter Class vehicle operating over a Midwestern state during restricted conditions would clearly not exceed the proposed TLS during the disaster response operations. This is because the population density is a fairly low value and the airspace density was set on the lower end of the spectrum due to the restrictions that would likely be put in place over the disaster area. This simulation, while fairly simple, does demonstrate the importance of conducting this type of realistic safety assessment process before conducting missions to truly understand the risk involved.

Although the major variables affecting the variability of the ground casualty rate in Figure 96 match closely with the border patrol scenario, there are a few other inputs that also appear. To a minor degree, the percentage of time that people spend indoors, the amount of land covered by buildings, and the amount of energy that commercial buildings can absorb before collapse also now appear. These variables indicate that for a medium to large vehicle operating in a moderately populated area, that the amount of protection that shelter provides is a more important factor in determining casualty rates.

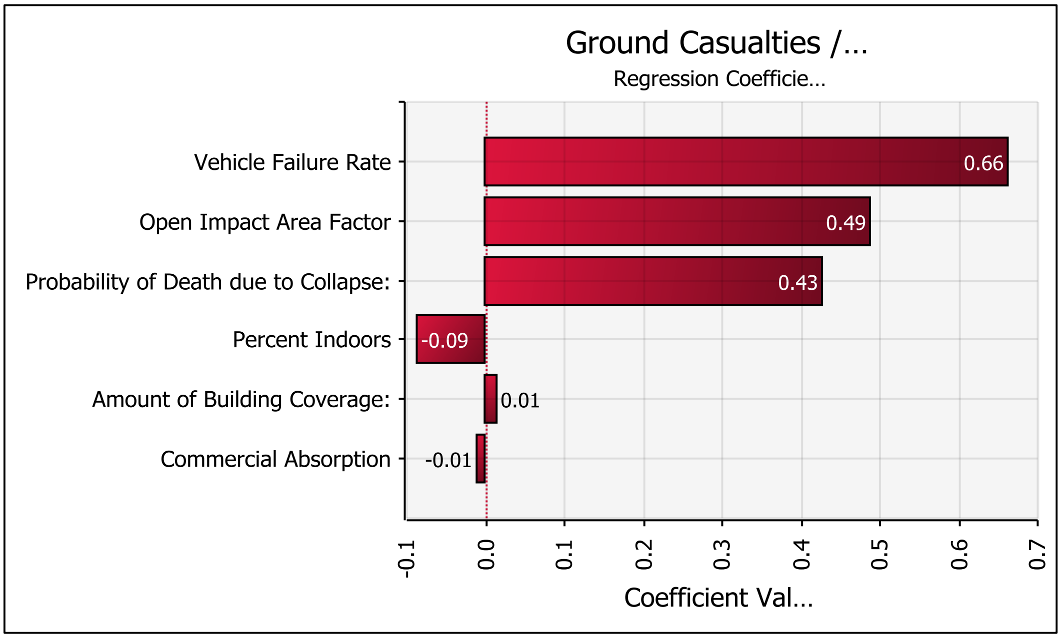


Figure 96: Sensitivity Analysis for Ground Casualties

Scenario 3: Urban Law Enforcement with 'Shadow-Class' Air Vehicle

Aircraft can offer law enforcement officials significant capabilities in terms of surveillance and situational awareness, yet an article on the subject cites that less than 3 percent of law enforcement agencies operate manned aircraft due to the prohibitive costs of purchasing, sustaining and manning these aircraft [224]. UAS can operate at a fraction of the cost of manned aircraft due to their lower weight, size, and complexity. A list of COA sponsors released by the FAA in early 2012 reveals that 16 of the 61 agencies requesting COAs for UAS operations are law enforcement related [28], indicating that law enforcement agencies are already operating UAS. To date, the majority are very small UAS, typically on the order of less than 25 lbs [224]. The purpose of this scenario was to explore the boundaries of safety by simulating a larger air vehicle for use in law enforcement operations over one of the most densely populated cities in very dense airspace.

There are three important factors to take into account when setting a TLS for the law enforcement mission. First, this mission has the potential to be routine if used for persistent surveillance purposes. Based on the aforementioned Monmouth University poll, while 80% were in favor of using 'drones' for search and rescue missions that number dropped to 67% for tracking runaway criminals and only 23% support using them for speeding tickets [49]. The director of the polling organization was quoted in the article as saying "Americans clearly support using drone technology in special circumstances, but they are a bit leery of more routine use by local law enforcement agencies" [49]. Therefore, the risk allowable by the public for more routine use is likely to be less than in scenario 2.

Second, the law enforcement mission for UAS has stirred privacy concerns among the public and has become a controversial issue. The AUVSI Code of Conduct specifically mentions the word privacy in their list of tenets under the heading of 'Respect' [65]. The same poll mentioned above asked about the public's concern about their privacy with respect to drones. Forty two percent of the people were 'Very Concerned' and an additional 12% were 'Somewhat Concerned' with only 31% being either 'Only a Little' or 'Not at All' concerned [49]. An informal review of articles written about UAS at the time of this thesis reveals a dichotomy. Industry articles are concerned with safety and technological advances such as SAA, while public articles focus almost exclusively on privacy concerns.

The third and perhaps most important, yet intangible point, is that the law enforcement missions represented by this scenario will most likely be conducted in urban areas. Despite UAS being cheaper to operate than manned aircraft, they still require funding for procurement, training and maintenance. By being focused in more urban areas, the UAS operations will also tend to be in areas of higher than average media coverage. Thus, any accident early in the integration stages over a city is likely to be spectacular and well-covered by local as well as national media.

Based on the main points above, it is reasonable to assume that the TLS for a routine law enforcement mission with privacy concerns associated with it would have a higher TLS requirement. For the purpose of this simulation, the TLS was set two orders of magnitude more stringent than the current manned aircraft fatality rate previously discussed.

After setting the TLS, the next step again in the process is to assess the initial safety level for the mission and environment in question with no mitigation measures in place. Unlike the previous simulations, the law enforcement scenario was modified slightly to better reflect some of the details of the New York City environment that simply were not available when dealing with a wider or more generic operational environment.

For example, instead of setting the information about ground coverage to more general values, data was obtained from land usage reports that details what portion of the ground in NYC is covered by open area, residential structures, or commercial and other buildings. The data, which appears in Table 46, was leveraged in the simulation to better represent the actual land usage for scenario 3.

Table 46: Land Use Statistics for New York City

Information	% of Land Area	Source	Citation
One/Two Family Housing	27.3	New York City Planning Website	[225]
Multi-Unit Housing	12.2		
Mixed Use Residential/Commercial	3.0		
Total Residential	***42.5***		
Commercial/Office	4.0		
Industrial/Manufacturing	3.6		
Transportation	7.1		
Public Facilities	6.9		
Total Non-Residential Occupied	***21.6***		
Open Space	27.0		
Parking	1.3		
Vacant Land	5.8		
Total Open Space	***34.1***		
No Data	1.8		

In addition to the ground data, information from one of the FAA's databases, OpsNet was available to better describe the type of air traffic in the vicinity of NYC. As expected, the area handles a much larger percentage of IFR traffic compared to the overall NAS due to the complexity of the airspace and the concentration of major airports. Therefore instead of the roughly 16% IFR rate used for the other simulations, 87.8% of the air traffic in the NYC area is IFR traffic [226].

The results for this simulation appear in Figure 97. Clearly, the extremely high ground density values and lower system reliability for the Shadow class vehicle have made this mission unacceptable with current technology and architecture. Based on this discovery, the next step would be to filter cases to determine what improvements need to be made in order to achieve the desired TLS.

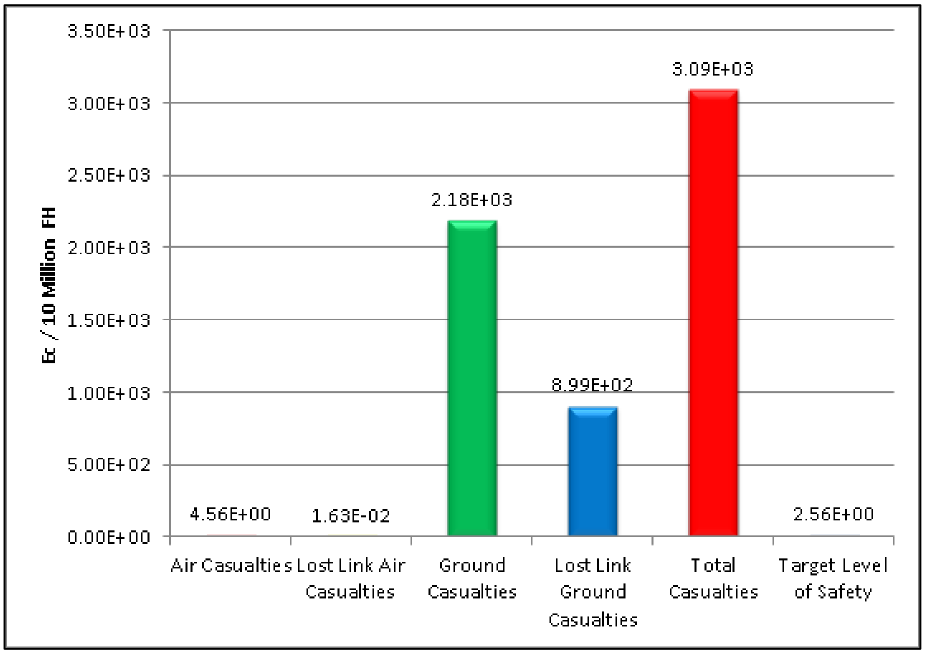


Figure 97: Initial Safety Assessment

In this particular case, filtering the cases out to determine those that meet the required TLS is not effective since none of the cases were close to the TLS. Clearly, the ground casualties for this scenario are driving up the total casualty rate to unacceptably high levels. The two factors most critical to the casualty rate are the population density, which cannot be controlled by the operator, and the overall system failure rate. While it would be desirable to set a more stringent system failure rate, there can only be a realistic expectation of improvement. In Figure 98 below, the DoD shows the improvements in mishap rates for major unmanned and manned aircraft systems over time. At best, the systems experience a reduction in mishap rate by approximately one to two orders of magnitude over a system life cycle.

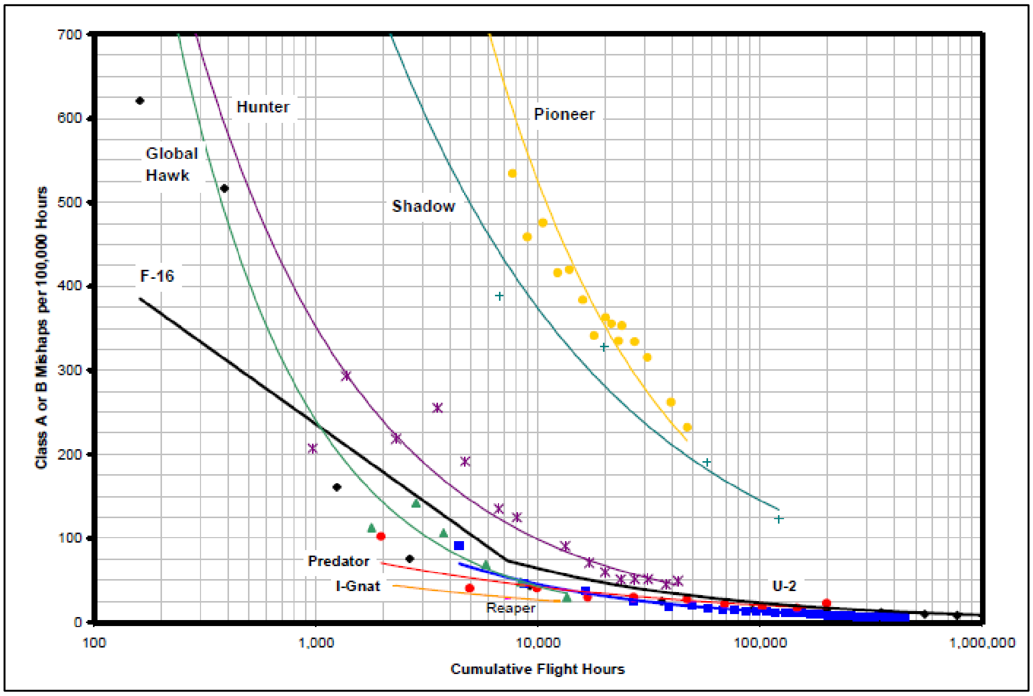


Figure 98: Aircraft Reliability Trends Over Time [4]

To gain additional insight into the third scenario, a sensitivity analysis was conducted. The analysis in Figure 99 and Figure 100 was conducted on the ground casualty rate for the urban law enforcement scenario with one variation. The analysis in Figure 100 featured an even lighter air vehicle than the scenario called for in the form of a Micro (1 Pound) scale UAS. The purpose was to see what variables were important when examining one of the smallest vehicles proposed in one of the most densely populated areas. During the Micro UAS simulation, the air vehicle was assumed to carry no fuel on board, this eliminating the possibility of possessing chemical energy in a crash sequence.

In the first graph, once again it is evident that many of the factors related to shelter and penetration become slightly more important to the outcome. Now the speed of the vehicle and the factor used to determine the descent speed, initially estimated at 1.4 from Dalamagkidis, also play a role. In addition, the chance of fire and time spent in residence all become minor factors in the response variability. This trend is amplified slightly for the 1 pound vehicle in Figure 100 as the ability to absorb energy for various shelters also appears in the regression. What these graphs show, as previously discussed, is that additional research is certainly needed to determine what degree of protection various forms of shelter provides so that the community can reach a consensus on reasonable ranges of shelter values for future TLS analysis. Given the importance of this problem and the relatively low cost of actual testing on mockup air vehicles and test structures, this further analysis should be conducted to further the process of understanding the risks posed by UAS operations.

This analysis also shows that the time of day that UAS operate over more populated areas can also play a role in determining UAS risk as more people tend to be under shelter in their homes during hours of darkness and especially late at night, according to the NHAPS study data.

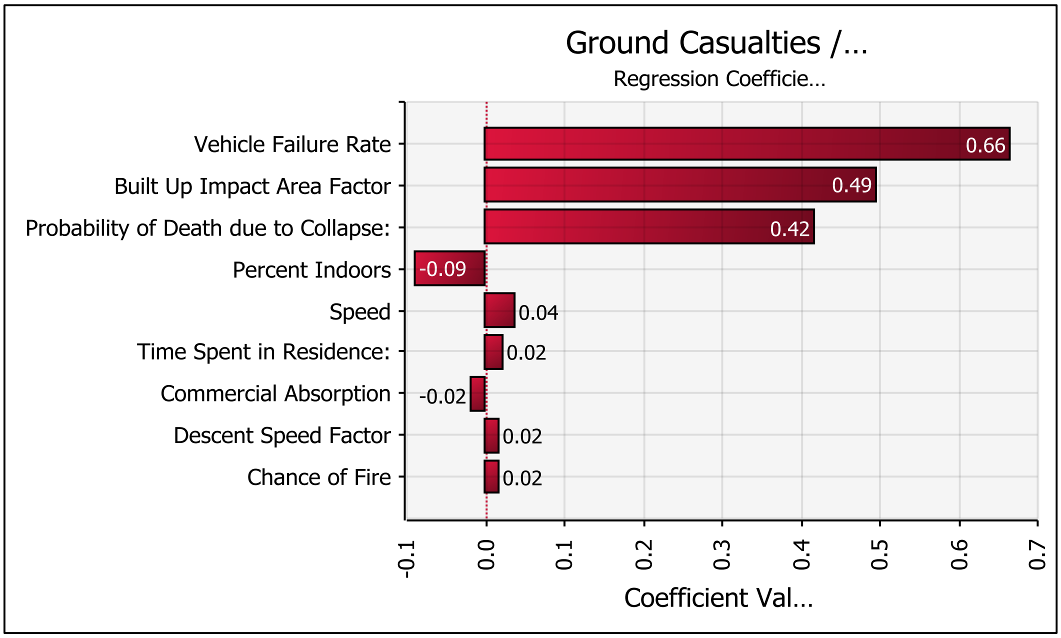


Figure 99: Sensitivity Analysis for Ground Casualties

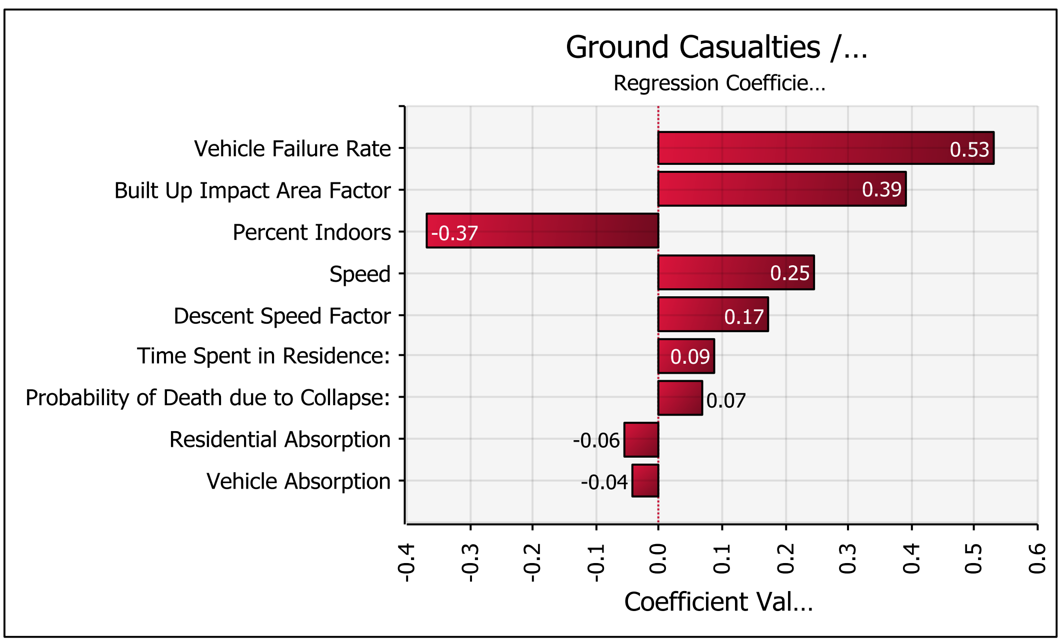


Figure 100: Sensitivity Analysis for Ground Casualties with Micro UAS

In order to determine the impact of reliability improvements in this scenario, the simulation was conducted again with an improvement in the system failure rate and link failure rate of one order of magnitude with no other changes. As expected, the casualty rates are reduced by an order of magnitude but remain two orders of magnitude greater than the TLS. The results appear in Figure 101. Since the scenario still does not meet TLS requirements the framework would move to the final step which is to evaluate mitigation measures. These measures were originally included in the event trees but have remained unused for the most part up until this point. Since the inhibiting factor is ground casualties, the mitigating steps will focus on the measure to move to a Safe area in the event of a lost link condition and the use of a parachute or similar impact attenuation device to reduce the energy the vehicle carries to the ground in the event of a system failure.

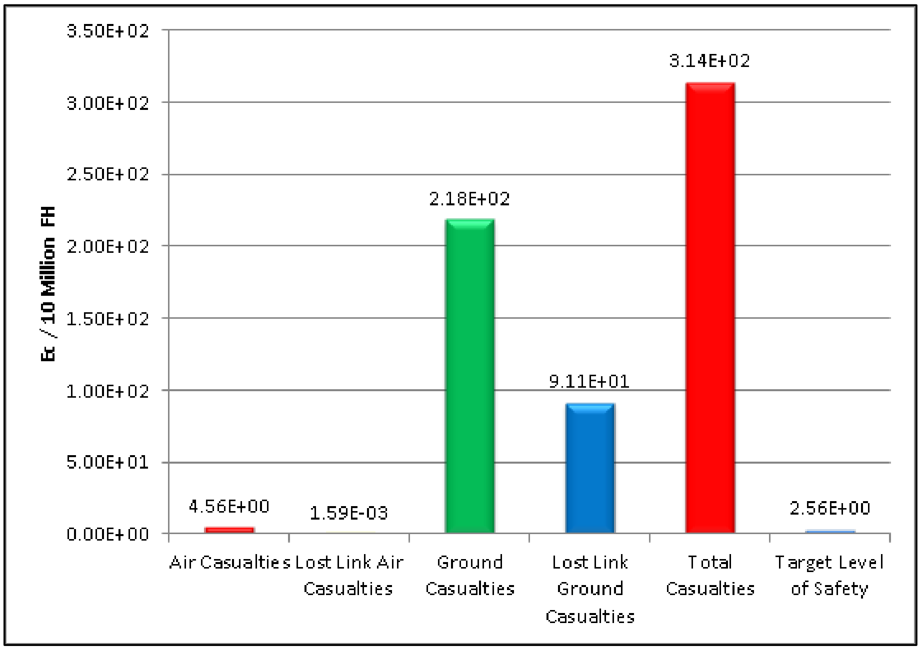


Figure 101: Safety Assessment with Improved Reliability for Scenario 3

At this point in the paper it is appropriate to discuss modeling mitigation measures in the event tree analysis. Any form of mitigation simply needs to be integrated into the logic of the event tree simulations. As mentioned in the concept sketch in Figure 23 on page 104, mitigation measures can be added to the event tree model between the operating environment and the effects. Included in the model of the mitigation measures is an effectiveness ratio that determines the likelihood that the mitigation performs its intended function.

Based on the analysis conducted on the law enforcement scenario, it is clear that ground casualties are the critical factor preventing the law enforcement scenario from achieving the desired TLS. Two methods that could mitigate some of the risk of ground casualties are the use of a parachute or other deceleration device to attenuate the impact of the air vehicle to reduce the risk due to system failures. Another technique is logic programmed into the software of a UAS that guides an air vehicle that has lost link to a pre-designated area that is less densely populated than the vehicle's operating area. The vehicle would then remain in this safe area until link can either be re-established or the air vehicle terminates flight due to a lack of fuel. Modeling these mitigation measures requires small changes to the event tree that can be analyzed for their effects. In the case of both measures, an effectiveness ratio can be used that sets how often the particular measure achieves its intended goal. The TLS approach can be used to set a required effectiveness ratio for the mitigation in question to allow the UAS to achieve a required TLS.

For the first mitigation measure, the use of a parachute device was added to the model as an example. The demonstration of the parachute mitigation device is also another way to highlight the advantage of using the event tree format for this framework. If the ground risk equations used in previous studies and in the simple model were still in use, there would be no direct way to estimate the effects of using the parachute to mitigate ground risk. However, with the event tree format, changes can be made directly to parameters in the model to determine the effects of these changes on the output, or casualty rate.

For the purpose of the calculations, the parachute had an effectiveness value that represents how often the system could effectively deploy in the event of a system failure that would render further flight impossible. The parachute deployment altered the effects model in two ways. First, the descent rate for the air vehicle was modified to reflect the deceleration that would occur when the parachute deployed. This changed the kinetic energy of the vehicle making it less likely to penetrate a building. In addition, the impact area calculation was changed from the weight-based calculation used typically in this model to a calculation based on the physical dimensions of the air vehicle. This last change was based on the assumption that an air vehicle descending via parachute would not cause a large impact area due to a combination of skidding and projecting fragments, but would settle to the ground in a more vertical manner.

The velocity value used in the model for the descent with a parachute was 28.33 feet per second. This value was based on a report from the Cirrus company on the parachute installed on their SR-2X aircraft [124]. This figure is deemed to be conservative because the Cirrus family of aircraft that use this aircraft are heavier than the UAS in question for this scenario.

However, despite these risk mitigation measures being implemented in the model, the risk for an urban law enforcement mission still exceeds the theoretical TLS set earlier in this phase. The results, seen in Figure 102, clearly indicate that the overall casualty rate for this scenario is still almost 20 times worse than required.

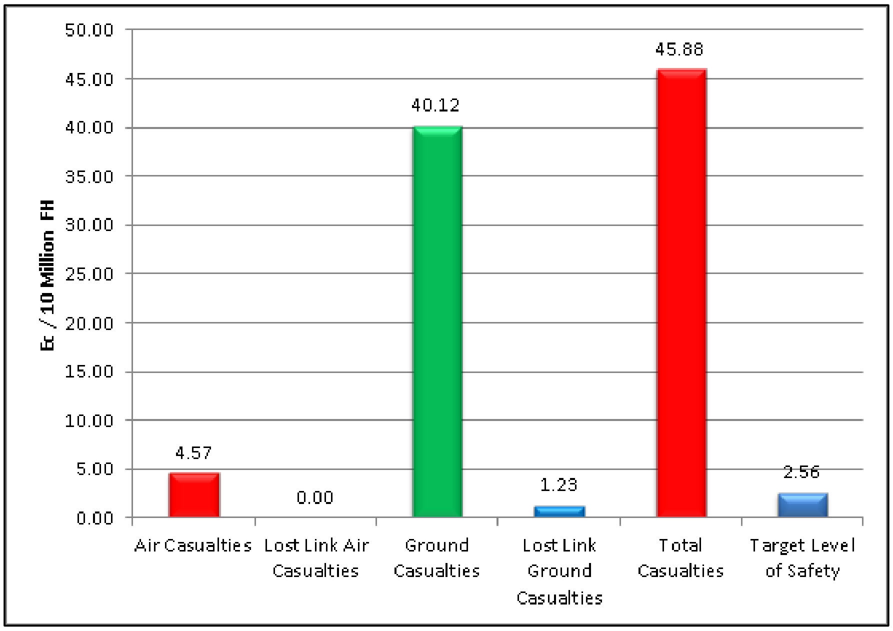


Figure 102: Safety Assessment with Ground Risk Mitigation Measures

The numbers above represent the mean E_c values from the model. Using the simulation data, one can examine individual cases from the Monte Carlo analysis. Filtering out the cases that do not meet the TLS, one can examine the mean value of the vehicle failure rate of all the cases that to meet the TLS. In this case, that value is 4.77 x 10^{-6} failures per hour. This is significantly better than the current Class A accident rates published for similar UAS used by the DoD as depicted in

Table 47. While some of the accidents in this table can surely be attributed to the harsher conditions and greater urgency with which the missions were flown by the DoD under combat conditions, it is unlikely that the civilian law enforcement application of a Shadow-class UAS would achieve an improvement of 3 orders of magnitude in failure or accident rates.

Table 47: Historical Class A Accident Rate

<table>
<tr><th>Information</th><th>Value</th><th>Units</th><th>Source</th><th>Citation</th></tr>
<tr><td>Global Hawk Class A</td><td>8.8×10^{-4}</td><td rowspan="5">Class A / FH</td><td rowspan="5">DoD UAS Roadmap</td><td rowspan="5">[4]</td></tr>
<tr><td>Predator Class A</td><td>2.0×10^{-4}</td></tr>
<tr><td>Hunter Class A</td><td>2.4×10^{-4}</td></tr>
<tr><td>Shadow Class A</td><td>1.91×10^{-3}</td></tr>
<tr><td>Pioneer Class A</td><td>2.81×10^{-3}</td></tr>
</table>

However, to fully demonstrate the implementation of mitigation measures, the scenario was continued to show the effects of inserting mitigation measures designed to reduce the risk of midair collisions into the model. For this purpose, the system reliability of the law enforcement UAS was assumed to improve to 1×10^{-6} failures per hour. This is to emphasize the air to air casualties in the scenario. When this change is made, the casualty results are dominated more heavily by midair collisions as seen in Figure 103. These values assume that the UAS has no inherent SAA capability, so the only avoidance that takes place is either due to airspace control measures, as in the case of the IFR traffic, or through the actions of other airspace users.

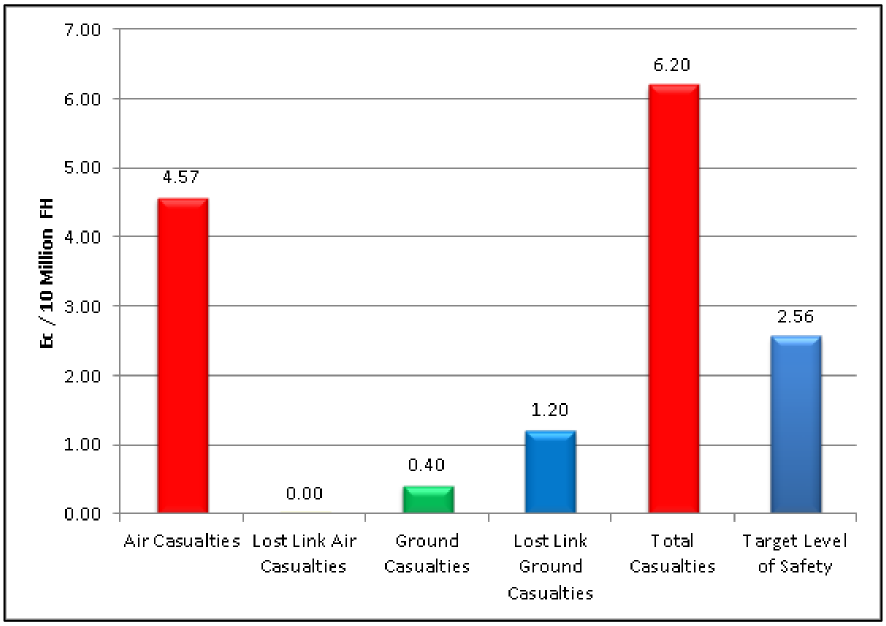


Figure 103: Safety Assessment with Improved System Reliability

Simply adding a SAA capability to the UAS model, with effectiveness ranges from 50% to 99%, the casualties caused by midair collisions are significantly reduced. The results are shown in Figure 104. While, overall the scenario would not meet the required TLS, the simulation does give stakeholders the ability to analyze the implementation of SAA and determine requirements for any SAA system requirements. Figure 105 shows a comparison of the overall casualty rate and Figure 106 shows a comparison of SAA effectiveness isolated against the Air Casualty rate alone.

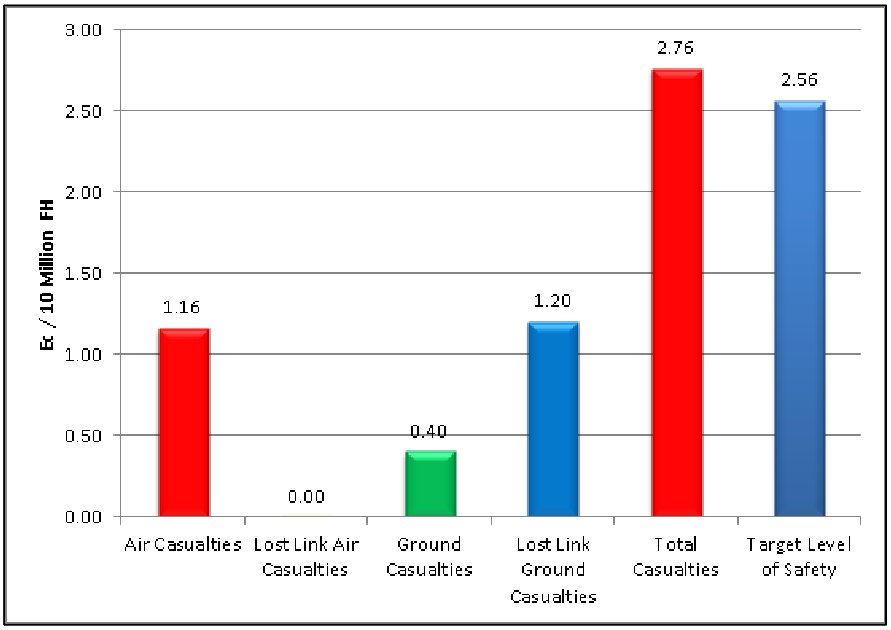


Figure 104: Safety Assessment with Improved System Reliability and SAA

The information shows how the effectiveness ratings in the model can be used to help shape standards for mitigations such as SAA. If the total casualty rate is limited to 2.56 casualties per 10 million FH, as depicted by the horizontal line in Figure 105, the data shows that with a theoretical 90% SAA effectiveness rating, approximately 32% of the cases were below the TLS. This is similar to a confidence level in that it shows how confident one can be in achieving the TLS, with the selected parameters.

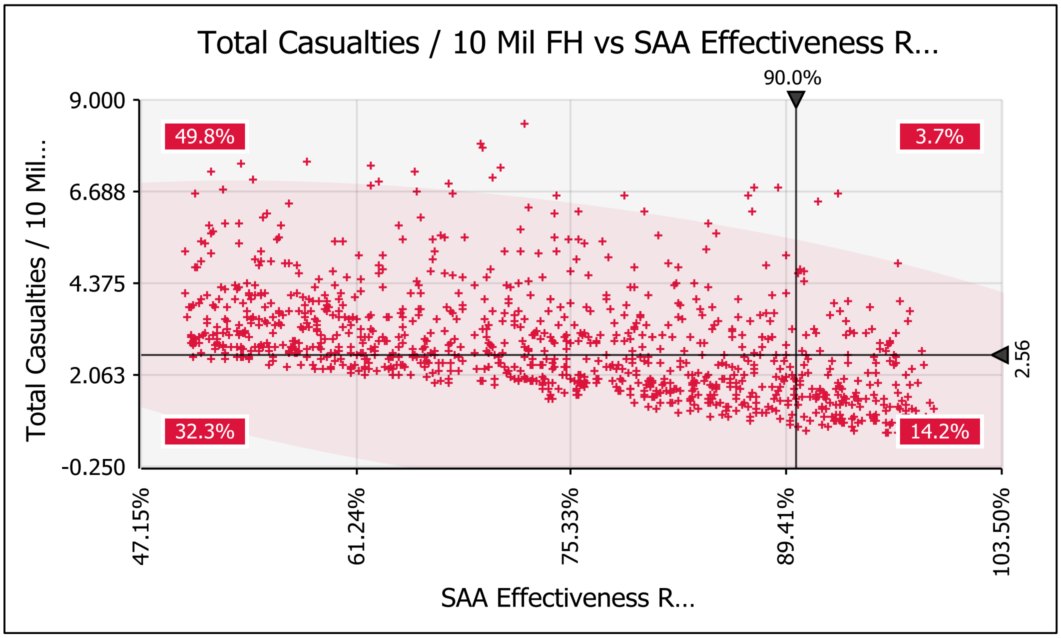


Figure 105: Casualty Rate vs. SAA System Effectiveness

Another way to look at this problem, which may yield more useful results, is to allocate the overall TLS set by administrators to both a ground TLS and midair collision TLS. This would allow stakeholders to more closely link the failure rates and mitigation effectiveness rates to the casualty rates caused by either ground or midair collisions. For example, when the SAA effectiveness is plotted against the air casualties alone, as in Figure 106, the relationship between the two is much clearer. This information could be used more effectively to set SAA effectiveness standards or the standards for any such system.

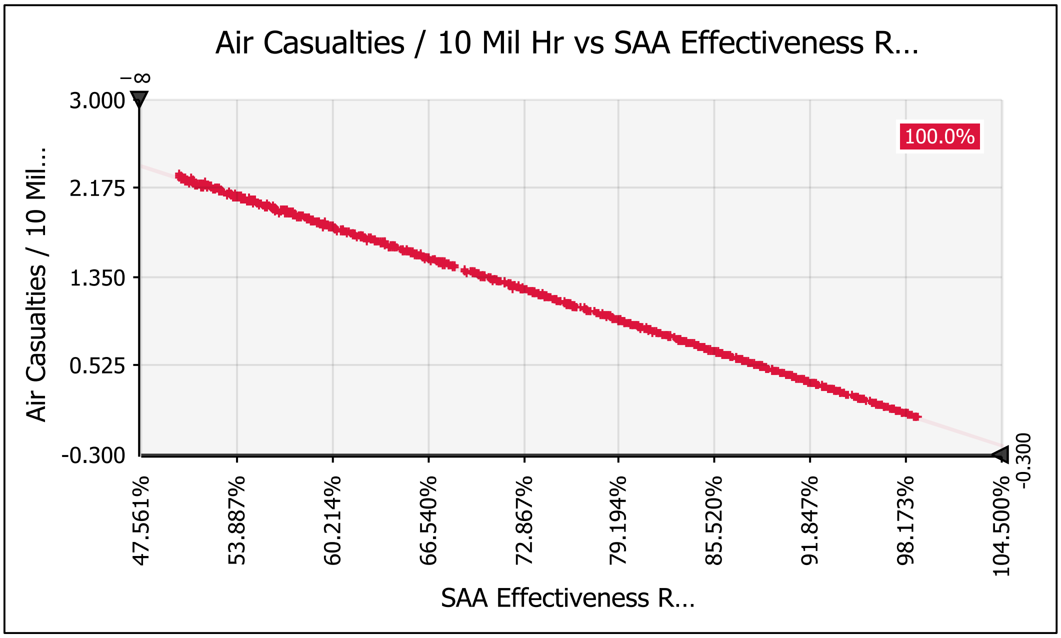


Figure 106: Air Casualty Rate vs. SAA System Effectiveness

The last type of analysis conducted for this scenario was to determine the impact of different methods of SAA on the air casualty rate. For this purpose the air density was increased to one of the highest levels possible, or 0.01 aircraft / nm^3. In addition, the link failure rate was increased to reflect current link failure rates for UAS. These measures were taken to emphasize air casualties. The results, which appear in Figure 107, reflect the midair casualty rate in casualties per 10 million FH for three cases. The first case assumes that the UAS does not have any inherent SAA capability and all separation is due to airspace control measures and avoidance on the part of the pilots in manned aircraft. The second case assumes that the UAS has some SAA capability but it is a ground-based system which means the UAS loses the ability to avoid collisions in the event of a lost link condition. The third case assumes that the UAS possesses an air-based SAA capability which could consist of an active system like radar or a passive system like ADS-B. In addition, the UAS has sufficient autonomy to permit it to avoid collisions during a lost link condition.

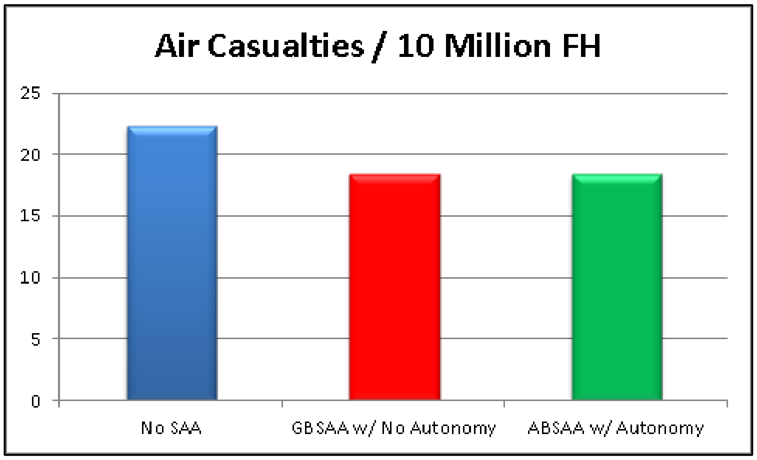


Figure 107: Midair Collision Casualty Comparison

The results of this experiment are very illuminating. First, adding any type of SAA system reduces the casualties in this scenario from approximately 22 to 18 per 10 Million FH. This is due to the fact that when an encounter does occur, the likelihood that a collision occurs is reduced because not both the pilot and the UAS are trying to avoid each other. However, there is only a minor difference in the rate between the GBSAA and the ABSAA experiments. This is because the likelihood of an air to air collision during a lost link condition is very remote. First, a lost link condition has to occur. Although not extremely improbable, the condition does not happen often. Then, during the time that the lost link condition is occurring, an encounter must occur. Again, NMACs occur historically on the magnitude of 1×10^{-6} per FH. Then, if an encounter or NMAC does occur, avoidance and separation on the part of ATC, the pilot, and the UAS must fail. Despite much of the attention that this topic has garnered, it is actually not a very probable scenario.

Applications to Certification

One of the goals in developing a TLS framework is to be able to utilize the framework to support the development of UAS certification standards. Burke's work covers a substantial amount of information on the link between the TLS approach and certification standards [93]. This work describes how the TLS value could be used to determine the requirements and rigor for UAS certification. It is not the intent of this work to cover the actual certification process in great detail for UAS, merely to demonstrate how the framework developed in this thesis could be used to determine system-level failure rate and effectiveness requirements.

It is important to note that the use of a TLS approach does not preclude also using some form of airworthiness codes as most organizations currently do. However, as pointed out in a CASA document on the topic, the TLS approach should be used as a prelude to any airworthiness standards development to ensure that any standards or requirements are linked to safety.

As discussed in the section on Defining the Problem, without the link developed in this framework between failures and casualties, any certification standard developed is not directly tied to safety and risk for UAS. As a result, any failure rate standards developed without this link in place could inadvertently be too conservative or not safe enough. In addition, the standards should include provisions to account for the operating environment to avoid penalizing UAS that are only intended to operate in remote areas.

Another challenge to UAS integration previously identified, is the lack of an agreed upon classification scheme. A summary of some potential categories appears below in Table 48.

Table 48: Certification Category Schema

UAS Characteristic	Ground Environment	Air Environment	Architecture
• Weight • Size • Energy • Mission • Based on similarity to manned aircraft	• Continuous Population Density • Categories of Density	• Operating altitude • Airspace Control • Class of Airspace • Aircraft Density	• Levels of Autonomy • Type of Control (LOS, BLOS)

Several previous studies have already discussed the need to develop UAS certification standards and some have been linked to risk or safety. Clothier, et.al. proposed an energy-based approach to defined certification categories based on whether UAS could penetrate different roof types [88]. However, in the course of this research it was found that all but the smallest of UAS are theoretically capable of penetrating even a concrete structure, based on energy calculations. As a result, this technique would only apply to very small UAS on the order of less than 10 pounds.

Dalamagkidis recommends several different certification techniques to include based on takeoff weight, operating altitudes, levels of autonomy, and risk factors. By adding operating altitude, this approach is taking operating environment into account. Altitude is a difficult metric to use for the certification process because airspace density values are not necessarily linked to altitude. For example, the airspace density at 1,000 ft of altitude over New York City would be vastly different than the density at 1,000 ft over a remote area in Montana.

King, et. al. also used the operating environment when determining maximum failure rates for UAS [227]. They delineate based on vehicle size and both population and air traffic density to determine standards. Weibel demonstrates an example of using the failure rates for UAS, linked to safety levels and population density in a report on UAS integration [91]. While linking reliability requirements directly to continuous values for population or airspace density is valuable from an analyst's perspective, it would make certification standards very vague and perhaps impossible to enforce. There would be no feasible way to determine an exact density value for any particular stage of flight.

A DoD report on UAS integration proposes standards based on the type of mission or operation, and access profile to the NAS [14]. This document lists access profiles such as vertical or horizontal transit of the NAS, visual line of sight, or operations within specified areas. This approach appears limited to a DoD perspective since this department can self-certify their UAS. In addition, the assumption appears to be that full integration is not close to realization. The difficulty with this approach is that specific UAS may be designed to accomplish more than one mission. Linking certification standards to missions or access profiles could unnecessarily complicate certification standards.

Finally, other sources have indicated a desire to simply certify UAS as close to manned aircraft standards as possible. That would mean that an unmanned vehicle that has the same size, weight and operating characteristics as a fixed-wing GA aircraft would be certified to the same standards as that type of aircraft, as an example. The research in this paper has already made the argument against this type of approach on a few grounds, mainly the differences between manned aircraft and UAS, the rapidly changing nature of UAS, and the fact that this approach penalizes UAS by requiring reliability standards not linked to safety levels. Another potential problem with this approach is that it can be counterproductive to safety. If UAS are required to meet all of the same certification requirements as manned aircraft, the operating weight of the air vehicles is likely to increase. This thesis has already shown that vehicle weight is an important factor that would drive up casualty rates if increased due to the larger impact area and higher kinetic energy.

Based on all of the analysis conducted, the author asserts that the best possible certification categories for UAS would be based on vehicle weight, categories of population density (rural, suburban, urban), and airspace class (B, C, D, etc.). These designations are made for the following reasons. Vehicle weight affects several aspects of the UAS that are all linked to safety. The weight of the air vehicle has a strong influence on the size of a potential impact area, kinetic energy on impact, wingspan, cruise speed, and endurance. All of these factors affect safety.

Population density categories are a convenient way to delineate population density levels without confusing the issue by trying to quantify the actual population density over any individual area. This metric would also indirectly link to the UAS mission since some missions are going to be more prevalent in certain population categories. For example, a gas pipeline survey mission is likely to be rural while a law enforcement mission is likely to be suburban or urban in nature. Also, the definitions of these population categories are published by the U.S. Census Bureau and can be standardized. Finally, using the existing airspace classes to set certification standards is convenient for a few reasons. One, the classes are already well understood and published on aeronautical charts. Two, the airspace classes already differ in their architecture (level of control), and by default their aircraft density. As a result, this classification actually takes several factors into account. Table 49 is an updated version of the information in Table 48 that indicates what certification categories are recommended and the corresponding sub-categories that they also take into account.

Table 49: Recommended Certification Category Schema

UAS Characteristic	Ground Environment	Air Environment
• Weight ○ Size ○ Energy • ~~Mission~~ • ~~Based on similarity to manned aircraft~~	• ~~Continuous Population Density~~ • Categories of Density (Rural, Suburban, Urban, City Center)	• Class of Airspace ○ Airspace Control ○ Aircraft Density • ~~Operating altitude~~

The purpose of the remaining portion of this section is to demonstrate the use of the models developed in this research to develop reliability and effectiveness standards that use these categories. As demonstrated in the SAfE-D framework, the first requirement to setting certification standards based on this framework is to establish a TLS. While the impact of setting a TLS was analyzed in Part 2, the societal reasons for setting a specific TLS were only briefly discussed in Part 3.

Based on the analysis conducted, it is the author's opinion that setting a separate TLS for ground and air casualties is more effective and logical. This policy does two things. First, by setting two distinct TLS, one for ground casualties and one for midair casualties, stakeholders can more effectively isolate required failure rate and effectiveness standards for distinct aspects of the overall unmanned system. Second, casualties on the ground are true bystanders who are members of society at large. On the other hand, other airspace users have chosen to take part in an activity that could lead to a midair collision. This is no different than when people currently choose to take flight and share the airspace with other manned aircraft, either as pilots of their own aircraft or as passengers. Society recognizes the difference between these two cases and typically sets safety standards differently.

For casualties caused by midair collisions with UAS other airspace users should at least expect UAS operations to be no less safe than current aircraft operations. According to statistics for a 20 year period, the death rate for all aircraft operations is the aforementioned 2.56×10^{-5} deaths per FH [178]. For ground casualties, which would entail bystander deaths, the metric is different. There are two different metrics that are most applicable for this case. One value that covers a similar 20 year period actually delineates the ground casualties caused by manned aviation. That value is 7.6×10^{-8} deaths per FH [176].

Another way to view this metric is to reference the guidance given by the RCC for fatalities caused by range operations to the public. They specify an annual casualty limit of 1×10^{-3} [27]. Based on previously discussed estimates for annual UAS usage, the RCC value would equate to 2.32×10^{-10} fatalities per FH. However, this requirement is extremely difficult to achieve and applied to operations that were more sporadic or one time use cases. As a result, for the purpose of this analysis, the value 7.6×10^{-8} was used.

In order to delineate population density values on the ground it is useful to link them to something that UAS users can view graphically and understand when planning flight operations. Different GIS packages can display map overlays with population density values. An example of this application is in Figure 108 with the corresponding density values in Figure 109. The map was obtained from ArcGIS online which uses U.S. Census data to calculate population density values. These values were cross-referenced to U.S. Census data to determine if the classifications were relevant.

Table 50: Population Density Values by Category

Information	People / mi^2	% of Landmass	Source	Citation
Remote	10	46	U.S. Census Data and ArcGIS Online Designations	[147, 177]
Rural	100	37.6		
Suburban	1,000	14.4		
Urban	10,000	1.9		
Metropolitan	25,000	<1		
Metropolitan City Center	71,564	0.0005		

Figure 108: Population Density by County

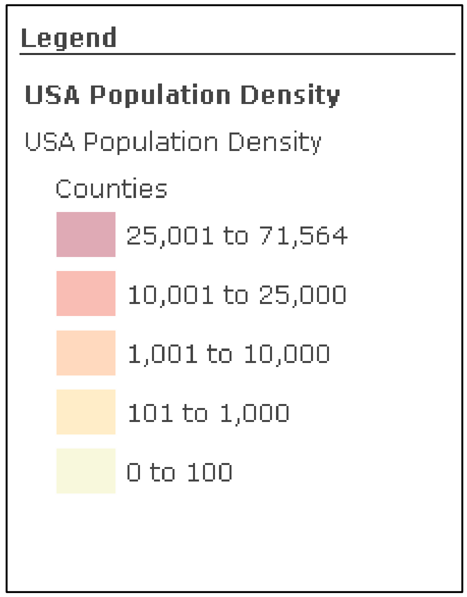


Figure 109: Legend for Population Density

In order to determine the airspace density for the different airspace classes, several pieces of information were required. In all of the cases, conservative values were chosen to analyze both a worst-case scenario and to allow for increases in the air traffic. For Class B airspace, there is no published maximum limit on the number of operations. As a result, information was obtained on Atlanta airport (ATL) since, at the time of writing, it is the busiest airport in the country [200]. To determine the airspace density, the number of aircraft operations per year was converted into an average value per hour, assuming a 16 hour day. The volume was calculated based on a 10 nautical mile ring extending to 10,000 feet. While Class B airspace extends beyond 10 nautical miles in different dimensions, there are no standardized dimensions and the 10 nm ring is the core part of the airspace.

FIG 3–2–1
Airspace Classes

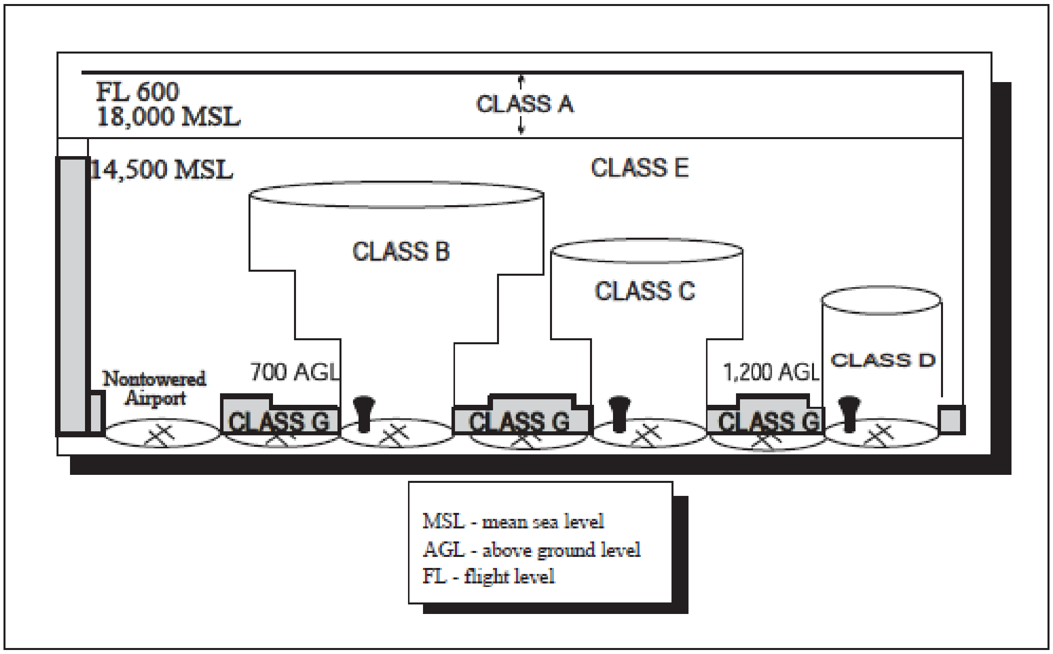


Figure 110: Airspace Class Diagram [228]

For the Class C and Class D airspace values, the volume was calculated from known airspace dimensions. The traffic was determined by examining the annual traffic requirements from Order JO 7400.2J that outlines the requirements of Class B and Class C airspace. For example, the requirement to designate Class B airspace was 300,000 operations per year. Thus the operations for Class C airspace were set at 299,999 per year for the purpose of calculations. The limit of 100,000 for Class C airspace was used to set 99,999 operations for the Class D calculations [229]. Class E airspace was grouped with Class D since there are no set dimensions for Class E, but there is often Class E airspace in use at Class D areas when the tower is not operational or in Class E extensions around Class D airspace. Thus separating the two was difficult. Finally, the density for Class G airspace was derived from the calculations used during the air risk model validation in Phase 1 of this thesis. This value was also viewed as conservative since the density values shown in Kochenderfer [102] for large portions of the U.S. outside major metropolitan areas show values up to three orders of magnitude lower. Finally, the Class A airspace was added and the airspace density was based on previous calculations for Class G airspace. The only major difference between Class A and Class G airspace in the model will be the fact that operations in Class A airspace must be under IFR rules, while Class G is uncontrolled. In addition, the airspeeds of potential intruder aircraft were increased for the simulations in Class A airspace.

Table 51: Airspace Densities by Class

Information	Acft / nm^3	Source	Citation
Class A	0.0012	Based on Calculations from Air Validation	N/A
Class B	2.55	Derived from Statistics on ATL Airport	[200]
Class C	1.76	Derived from Definition of Airspace Classes	[229]
Class D/E	0.73		
Class G	0.0012	Based on Calculations from Air Validation	N/A

The final set of categories that must be designated is air vehicle weight. There are several different classes of UAS already in use, as discussed in the Background section. Based on the fact that the DoD is currently the largest user of UAS and the fact that most UAS will likely be derivatives of these systems in the future, the group system described in Figure 3 on page 14 is a likely starting point for a category system. The groups below also combined aspects of the classification system described in different sources to ensure a wider basis of vehicles was covered. Both of these classification systems required augmentation based on the recent FAA modernization law and the need to further delineate the Group 4 and Group 5 vehicles used by DoD. Therefore a smaller group was added and upper limits were defined for Group 4 and Group 5 based on the largest air vehicles currently in those groups. The upper limit for Group 3 is the same as the upper limit for the EASA Very Light classification [230]. The upper limit for Group 4 is fairly close to the 150 kg limit outlined in several European certification documents [41].

Table 52: UAS Categories by Weight

Group	Weight (lbs)	Source	Citation
Group 1 (Micro)	< 1	N/A	N/A
Group 2 (Mini)	1.1- 4.4	FAA Law	[12]
Group 3 (Small)	4.5 - 55	FAA Law, DoD, EASA Drafts	[12, 14, 230]
Group 4 (Tactical)	56 - 351	ICAT Study, EASA Drafts	[41, 91]
Group 5 (Medium)	352- 1320	DoD	[14]
Group 6 (Large)	1,321 - 10,000	Based on Predator C	[135]
Group 7 (Heavy)	10,001 – 25, 000	Based on Global Hawk	

In addition to selecting the above groupings, based on as much similarity as possible with existing schema, a comparison was made between the weights associated with the groups above and the ability of the various structure materials described in Table 11 to absorb energy. Using the relationship between typical UAS air vehicle weights and their corresponding airspeeds from Table 7, a comparison of the ability to absorb kinetic energy for each applicable building material to the weight above which could penetrate the structure was conducted.

Table 53: Maximum Vehicle Weight for Building Materials

Building Material Type	Maximum Vehicle Weight (lbf)
4” Reinforced Concrete	57.0
2” Lightweight Concrete	11.7
Wood Panelized	3.5
Steel (Automobile)	1.2

What the data in Table 53 indicates is that vehicles in groups 1-3 should be incapable of penetrating structures that exhibit the same ability to absorb energy as 4” reinforced concrete. This is an important observation for the smaller law enforcement vehicles operating in highly urban environments. The maximum vehicle weight incapable of penetrating wooden structures, typical of many suburban and rural residential buildings, is 3.5 lbs which is fairly close to the 4.4 pound upper limit for Group 2 air vehicles. If Group 2 vehicles are limited to approximately 47 knots of cruise speed, these vehicles would also be incapable of penetrating these residential buildings. Finally, the 1.2 pound limit for vehicle penetration is very close to the upper limit for Group 1 vehicles.

To develop failure rate requirements for UAS, the following procedure was conducted. For each combination of UAS weight and population density in Table 54, a simulation was conducted using the ground risk model. The software was used to determine the maximum system failure rate for each combination that would ensure that the vehicle in question would not exceed 7.6×10^{-8} deaths per FH. The values throughout Table 54 are those maximum system failure rates. The green cases represent failure rates that meet or are below current UAS failure rates, based on the historical data cited throughout this paper. In other words, if UAS characteristics of the current UAS used by DoD were used in the weight and population density combinations in green, those systems should be able to meet the required TLS with no mitigation necessary. The yellow boxes represent a required improvement in the system failure rate of one order of magnitude, compared to the same historical rates. It is possible that since historical UAS failure rates in question are largely based on DoD usage in combat situations that an improvement of one order of magnitude could be seen by civilian UAS operators. When UAS missions are conducted by DoD in combat situations, it is likely that additional risks are taken with respect to weather, maintenance, and operating conditions that would not be necessary for civilian operators. The red boxes indicate combinations that would require two or more orders of magnitude improvement in system failure rate. This level of improvement is unlikely without more significant changes in UAS design and operations in these boxes would require risk mitigation measures and / or significant improvements in failure rates to achieve the TLS.

Table 54: Maximum System Failure Rates to Meet Ground TLS

Group	Remote	Rural	Suburban	Urban	Metro	City Center
Group 1 (Micro)	1.20×10^{0}	1.20×10^{-1}	1.50×10^{-2}	1.50×10^{-3}	6.01×10^{-3}	2.10×10^{-4}
Group 2 (Mini)	2.73×10^{-1}	2.73×10^{-2}	3.42×10^{-3}	3.42×10^{-4}	1.37×10^{-4}	4.77×10^{-5}
Group 3 (Small)	7.31×10^{-3}	7.31×10^{-4}	9.14×10^{-5}	9.14×10^{-6}	3.66×10^{-6}	1.28×10^{-6}
Group 4 (Tactical)	1.15×10^{-3}	1.15×10^{-4}	1.43×10^{-5}	1.43×10^{-6}	5.73×10^{-7}	2.00×10^{-7}
Group 5 (Medium)	3.05×10^{-4}	3.05×10^{-5}	3.81×10^{-6}	3.81×10^{-7}	1.52×10^{-7}	5.32×10^{-8}
Group 6 (Large)	4.02×10^{-5}	4.02×10^{-6}	5.03×10^{-7}	5.03×10^{-8}	2.01×10^{-8}	7.03×10^{-9}
Group 7 (Heavy)	1.61×10^{-5}	1.61×10^{-6}	2.01×10^{-7}	2.01×10^{-8}	8.04×10^{-9}	2.81×10^{-9}

Mitigation Criteria Development

One area that this framework can certainly provide input for is the development of standards for risk mitigation techniques. Two of the risk mitigation techniques previously discussed that bear further examination are Sense and Avoid and a method to reduce the effects of a ground impact. To demonstrate the use of these measures in the model, three experiments were conducted. First, the TLS concept was used to determine SAA effectiveness requirements based on the combinations of UAS and airspace categories outlined above. Second, the overall effect of including a parachute device in the ground risk model was examined. Finally, the effect that modeling a SAA system as either ground-based or air-based has on casualty rates under lost link conditions is examined.

SAA Effectiveness

An experiment was conducted using the air risk model set to achieve the required TLS of 2.56 x 10^{-5} fatalities per FH. In this case, the system's SAA effectiveness was varied in order to achieve the desired TLS. The values in the boxes in Table 55 represent those effectiveness requirements. The values were compared to publish values of TCAS effectiveness, since TCAS is one type of avoidance system already in use. Green boxes actually required no SAA system on the UAS because the combination of air density, vehicle size, and airspace architecture was such that the UAS did not need an organic SAA system to achieve TLS. Yellow boxes indicate combinations where the required SAA effectiveness was either near or below previously published TCAS effectiveness values. Finally, the red boxes required a SAA system better than published TCAS effectiveness values to meet the TLS and would require additional risk mitigation. The black boxes represent combinations that are unlikely to occur and were not considered. Since Class A airspace starts at 18,000 feet in the United States, it is not a likely operating environment for all but the larger UAS.

Table 55: SAA Effectiveness Required to Meet Air TLS

Group	Class A	Class B	Class C	Class D/E	Class G
Group 1 (Micro)		80.2	71.4	30.9	*
Group 2 (Mini)		80.3	71.5	31.0	*
Group 3 (Small)		90.8	86.7	68.1	*
Group 4 (Tactical)		91.1	87.1 %	68.9	*
Group 5 (Medium)		91.7 %	88.1 %	71.3 %	71.0 %
Group 6 (Large)	*	99.8 %	99.7 %	99.3 %	99.6 %
Group 7 (Heavy)	*	99.9 %	99.9 %	99.7 %	99.9 %

* Scenario met TLS without SAA capability required on UAS

The effectiveness values for the Group 6 and Group 7 vehicles are fairly high for Class B through Class G airspace. These values for avoidance are based on the model and with the assumption that other aircraft in the airspace are using visual avoidance only. This is a worst-case scenario since some portion of the other airspace users would likely have some form of electronic avoidance system such as TCAS or ADS-B as well. However, adding that parameter to the model at this time would have also required an estimate of the percentage of other airspace users using cooperative or compatible equipment. That would have created another variable that would have made the SAA effectiveness rating dependent on the percentage of cooperative traffic. As a result, that was not modeled in the system in order to determine a maximum value required for SAA effectiveness.

However, the studies on TCAS effectiveness discussed earlier in this paper indicate that even with two aircraft equipped with TCAS, the risk ratios compared to no aircraft equipped with TCAS only go as low as approximately 1% [101] or as high as approximately 5% [123]. Therefore, additional control measures or stronger avoidance measures would have to be studied and implemented prior to allowing the air vehicles in question to operate in these environments.

Ground Impact Mitigation

As discussed in Part 3, information for modeling the use of a parachute to reduce ground impact was obtained from the Cirrus corporation that has successfully incorporated parachutes into their general aviation aircraft. Assuming that the descent velocity is comparable to the value published for their device and the impact area is reduced from the weight-based value to a geometry-based value, the following results are obtained. The simulation considered a range of UAS vehicle weights and used a reasonable range for population density values, failure rates and vehicle dimensions.

When the experiment was conducted, the ground casualty rate experienced an approximately 25% reduction when modeling a parachute system compared to the simulation without a parachute. A t-test of the two sets of results indicates that there is sufficient evidence to reject the null hypothesis that the two means were equal.

Table 56: Values for Parachute Mitigation Comparison

Variable	Value	Units
Assumed Parachute Effectiveness Rating	85-99	%
Mean Ground Casualty Rate With no Mitigation	$7.42x\ 10^{-6}$	Casualties per FH
Mean Ground Casualty Rate with Mitigation	5.6×10^{-6}	
Difference in Casualty Rate	24.62	%
p-Value for t-test of Means, assuming Unequal Variance, two tail	< 0.0001	N/A

Effects of SAA Location during Lost Link

A similar experiment was conducted with the SAA system to determine if the model would produce results significantly different enough when comparing a ground-based SAA system with one that is air-based. Both types of systems have been in testing with the U.S. Army and U.S. Air Force, respectively. The difference in the logic in the event trees is that, under lost link conditions, a GBSAA system will not be able to provide any avoidance guidance to the air vehicle. As a result, the SAA capability is essentially lost during lost link occurrences.

Table 57: Values for SAA Mitigation Comparison

Variable	Value	Units
Assumed SAA Effectiveness Rating	85-99	%
Air Casualty Rate under Lost Link w/ ABSAA	6.17×10^{-5}	Casualties per FH
Air Casualty Rate under Lost Link w/ GBSAA	3.83×10^{-4}	
Difference in Casualty Rate	83.89	%
p-Value for t-test of Means, assuming Unequal Variance, two tail	<0.0001	N/A

To further demonstrate the differences between the GBSAA and ABSAA scenarios, a more specific experiment was performed. This scenario featured a Medium-sized UAS operating in Class C airspace to determine how the lost link air casualty rates would differ for the two systems. The results, which appear in Figure 111, again show a significant difference in the casualty rate between the two systems. Clearly, this would be valuable input to any tradeoff study when deciding between the two systems.

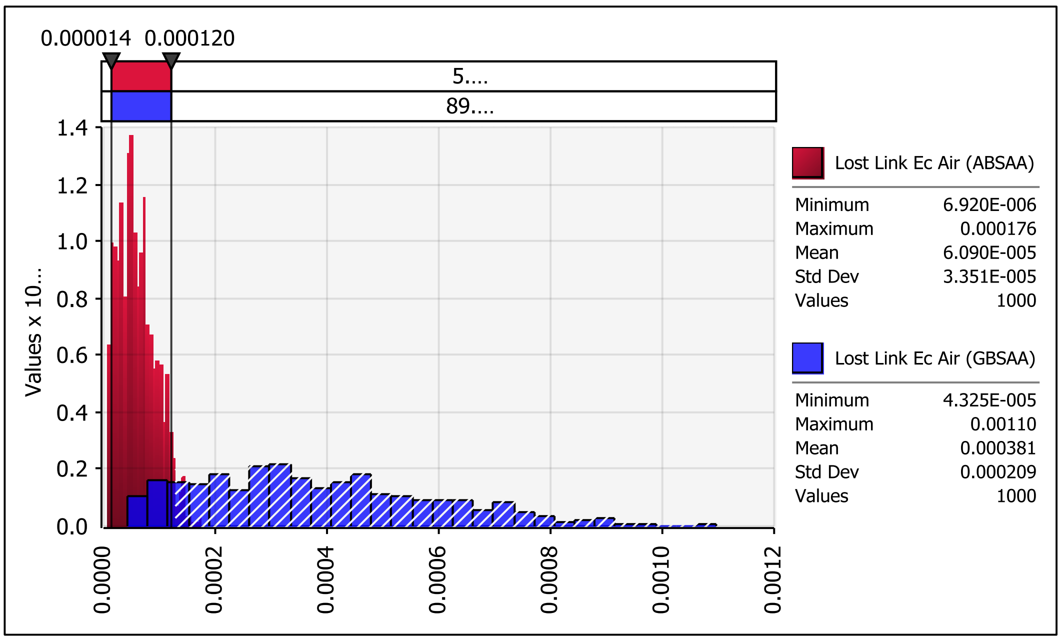


Figure 111: Lost Link Air Casualty Rate (Medium UAS in Class C)

Applications Beyond Certification

In addition to certification, another challenge to UAS integration identified in the Motivation section is operator training. Although this is largely an administrative issue, the framework outlined in this research can actually facilitate dialogue in this area. The advantage of the event tree format for this problem is that the initiating event for a potential fatality can be more than just a system failure related to reliability. Human factors can account for a portion of the system failure rate used to develop the safety assessment.

For example, the values in Table 54 demonstrate the maximum allowable failure rate, based on the vehicle and environment, to avoid exceeding the TLS. Human factors analysis can be conducted to estimate a failure rate due to human error that could cause a failure that could also generate casualties. Based on this analysis, two things would occur. One, the allowable system reliability would be modified to account for the reduced failure rate now allowable for reasons other than human error. Then, the training and certification for operators could be designed in such a way as to try and ensure that the human error rate does not exceed the allowable rate.

In Figure 112, the FTA diagram from Figure 9 is reviewed. To put the human factors discussion in context, if the required system failure rate is set by the TLS approach, then that failure rate can be allocated from right to left to several different failure sources. One of those sources can be human error and analyzed accordingly for impact. For example, the Defense Science Board attributed 17% of all UAS mishaps to human error [165]. This value could be used as a starting point to allocate failures to human error and then training and certification could be designed around reducing that value.

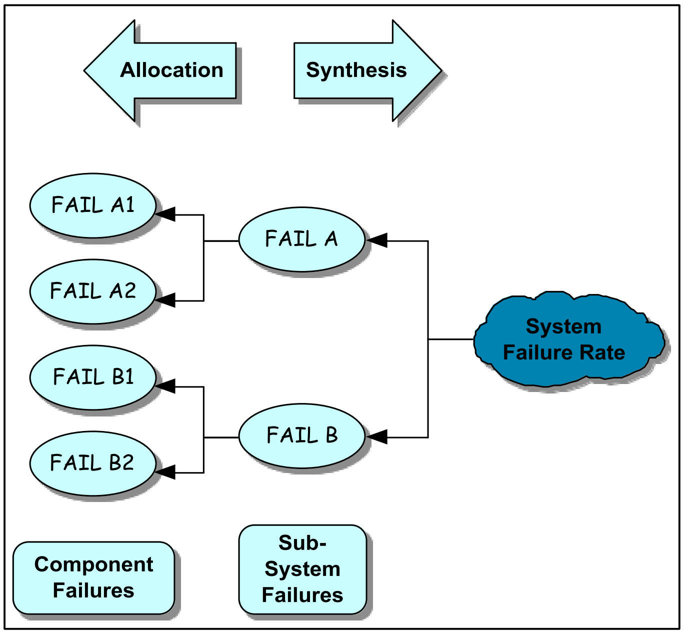


Figure 112: Fault Tree Review

An additional application for this type of approach is with regards to weather effects. Weather was not included in this model, however, it could also be included as a type of failure adding to the system failure rate. While data on UAS weather-related mishaps is difficult to quantify because much of the UAS flight time has been conducted by the DoD in contingency operations, NTSB statistics attribute as much as 20% of all GA fatalities to weather [145, 215]. Again, this could be an additional factor in the system failure rate that is subtracted from the allowable system failure rate. The remainder would be the allowable failure rate for the system itself. If weather effects are mitigated by restricting flight into certain conditions, then this value would be reduced, allowing for a higher system failure rate. Ultimately, floor values for certain factors such as weather or human error could be set by administrators. Then, UAS developers would have to show that their vehicle and system could meet the remaining failure rate allowed by the TLS approach.

CONCLUSIONS

There are several important contributions that can be drawn from this research, which generally apply to one of two categories. In the first category are conclusions drawn about the framework itself and in the second category are conclusions that can be drawn from using the framework about the nature of UAS operations and integration.

First, it is important to note that it is possible to predict casualties caused by UAS operations using existing data and information. This is a critical first step in establishing any type of safety assessment, risk reduction studies and an integration framework. Returning to the original problems preventing inhibiting integration, if one cannot accurately predict UAS safety after setting a target or goal, the TLS approach to this problem is untenable.

Developing the models for the framework also revealed several key factors about the parameters that contribute to risk. The sensitivity analysis for the ground risk model indicated that UAS weight and population density were the two parameters that contributed most to the variability of the casualty rate. This information was useful in developing a concept for certification standards that relied on seven UAS weight and six population density categories.

Also evident in the development of the ground risk model was the importance of the method used to predict the size of the impact area caused by an air vehicle crash. This topic is discussed in more detail in the Future Work section. Also, the degree to which including population behavior patterns into the risk model changed casualty rate results was illuminating. Any risk prediction model should include realistic behavior patterns for people into the population density metrics to adequately capture how people spend their time whether it be under shelter or in the open.

The air risk model revealed that UAS size was a critical parameter as well as aircraft density and factors related to the operational architecture UAS operated under. These discoveries led to an effectiveness scheme for SAA that relied on the UAS size categories and existing airspace classes. Airspace classes combine aircraft density and aspects such as whether the traffic is controlled into one category.

After using the casualty prediction capabilities developed for this research, it is possible to draw several conclusions about UAS operations. First, despite their small size, UAS in the 55 lb range are not safer than manned aircraft in all operating environments. Some measure of mitigation or operating restrictions would need to be set in place to achieve desired TLS levels. Second, applying manned failure rate standards to UAS does not necessarily make sense, given the difficulty UAS developers would have reaching these levels and the fact that doing so would unfairly require UAS to be safer than their manned counterparts. Using TLS values instead, it can be concluded that failure rate standards for UAS could actually be set along a range differing by as much as ten orders of magnitude, based on UAS size and population density.

To properly account for the risk associated with lost link conditions, a metric must be utilized that captures both the frequency and duration of lost link events. The experiments in this research showed that a link failure rate is insufficient to predict risk. The combined metric, similar to availability, should be the standard to which the link sub-system of UAS is designed to. Similarly, for SAA, the effectiveness metric should be used as a design standards. Effectiveness, which combines the reliability and efficacy of the system, is needed as a starting point to determine performance standards for any SAA system. For example, a Group 2 UAS in Class B airspace required a SAA system to be 80.3% effective in avoiding midair collisions. Since Class B airspace has a value for aircraft density associated with it in the model, then the SAA system can be designed with a particular number of potential intruders in mind. The Class B airspace also had a distribution for airspeeds of other traffic. When combined with the airspeed and maneuverability of the air vehicle in question, specific performance standards for the SAA system can be developed that include the distance with which the system must detect intruders, the time in which the system must trigger avoidance, and the accuracy of the detection capability.

Review of Framework Criteria

Earlier in the paper six criteria were introduced from Clothier that outlined what an effective framework for UAS regulations. These criteria are reviewed with respect to the framework identified in this paper. First, the TLS approach outlined is Justifiable since any reliability requirement, effectiveness standard or operating restriction is directly linked to the safety of the public and other airspace users. Designers and operators can be assured that any cost incurred to meet standards is justified to meet safety concerns and not based on a lack of understanding of UAS risk.

The approach is flexible and can account for a variety of UAS. New categories of UAS can be added to the analysis at any time, and the categories themselves provide operators with enough flexibility in terms of where they operate the aircraft and how they make tradeoffs to meet safety standards. For example, an operator can choose to either increase reliability or add mitigation measures to meet safety requirements.

This approach is systematic and objective. All of the data used in the framework is based on scientific principles. In addition, at any time the data used can be augmented with feedback from higher fidelity studies yet remain simple and effective because of the event tree format and statistical approach to safety. This framework is practical to use and practical in is application. As discussed before, the intent of this thesis was to implement a framework using commercially available software and in a user-friendly format. That goal was accomplished. In addition, the results are practical to implement because the final categories are based on a standards set of weight categories, airspace classes, and broad population density ranges.

Finally, this approach reduces the need for undue regulations by not having to create an extensive set of airworthiness codes for a rapidly changing industry. In addition, it avoids penalizing UAS by requiring them to meet manned aircraft standards when this research has already shown that this would make UAS safer than manned aircraft are.

Review of Objectives

As discussed in the Research section, this thesis attempted to achieve several objectives related to the overall problem of predicting UAS safety. A graphical review of those objectives appears in

.

Table 58: Research Objectives Review

Objectives	Met?
1. Develop a Framework	
- 1.a. Use available software tools	
- 1.b. Use credible supporting data	
2. Demonstrate implications of Framework	
- 2.a. Determine current level of safety	
- 2.b. Determine impact of using manned reliability levels	
- 2.c. Demonstrate effect of various TLS on UAS reliability	
3. Demonstrate applications of Framework	
- 3.a. Determine maximum vehicle failure rate	
-3.b. Determine maximum link failure rate	
-3.c. Determine minimum SAA effectiveness	
-3.d. Determine crash impact mitigation effectiveness	

Objective Met	Objective Partially Met	Objective Not Met

Overall, the first objective was to produce a framework to facilitate UAS integration and to include within that framework the capability to predict casualties caused by UAS operations. That prediction capability needed to include factors such as UAS characteristics and the environment in which UAS operated in. That objective was met by using the event tree format and data from existing studies related to the various branches in the event trees. In the process of building this capability, an examination of the state of the art in casualty prediction techniques was conducted as well. It is important to note that the prediction method created for this thesis was not only able to predict casualties more accurately than other methods, when compared using manned aircraft historical data, it also allowed for more flexibility because of the more complete use of the event tree concept.

The purpose of Objective 2 was to demonstrate the implications of having the capability to predict casualties caused by UAS operations in a variety of operating environments. First, the safety of the 4.4 and 55 lb UAS cases from the language in the 2012 modernization law were assessed. In addition, analysis was conducted on the effect that setting UAS failure rate standards to manned aircraft standards would be. Finally, the effect of mandating various TLS levels was assessed.

The real goals in Part 3 was to demonstrate how the overall framework could be used to assist stakeholders in making decisions about the integration process. The framework was used to assess specific use cases and determine the need for and impact of risk mitigation measures. Additionally, the framework was used to set recommended failure rate and SAA effectiveness standards. Objective 3.b. was assessed as being unmet because, as the model was explored, it was determined that it was impossible to determine link failure rate requirements to meet TLS values in isolation. A second metric, the mean time to reestablish link, was required and discussed. The combination of those two metrics could be used to determine the ability of the UAS to meet TLS using the concept described in Figure 91. Objective 3 was considered partially met because of objective 3.b.

Review of Hypotheses

In addition to the objectives listed above, the purpose of this research was to prove or disprove several hypotheses. Although each hypothesis was discussed in detail throughout the paper, the table below summarizes the hypotheses and the results of investigating each one.

Table 59: Hypotheses Review

Hypothesis	Outcome
1. UAS safety levels can be predicted from failure rates to within an order of magnitude.	Predicted to within 1 %
2a. UAS at the 4.4 Lb and 55 Lb sizes can already meet or exceed manned aircraft casualty rates at current reliability levels.	One Order of Magnitude Less Risk for 4.4 Lbs 55 Lb Vehicle More Risky
2b. Requiring all UAS to attain the same system failure rates as manned aircraft (1×10^{-6} to 1×10^{-9}) would penalize UAS designers and operators.	1-7 Orders of Magnitude Safer
2c. Mandating TLS levels more stringent than historical manned aircraft will unnecessarily restrict UAS operations.	81 % allowed at 1×10^{-5} 44 % at 1×10^{-6}

The first hypothesis dealt with the ability to accurately predict casualties caused by UAS operations. To test this hypothesis data from manned aircraft operations was substituted for UAS operations due to the lack of available UAS casualty information. For third-party risk, tests were conducted using both GA and Air Carrier data. For the second-party or air risk, data from GA operations was used solely. In each case, a test was conducted using the historical casualty rate as a hypothetical mean and compared to the experimental data from the appropriate model. In each case, the test was unable to disprove the null hypothesis that the means were the same.

Hypothesis 2.b. was that the 4.4 and 55 lb UAS mentioned specifically in the 2012 FAA law would be safer than historical casualty rates from manned aviation. Experiments were conducted using the specified weights of the UAS, failure rates characteristics of current, small UAS and a population density continuous distribution representative of the United States. Based on the results of the experiment, it was concluded that the 4.4 lb UAS would achieve casualty rates significantly lower than historical manned third-party rates. However, the same could not be said for the 55 lb vehicles. These experiments also assumed no additional risk mitigation measures in place.

The third hypothesis was that using manned aircraft failure rates for UAS would be unfair by indirectly mandating safety levels more stringent than historical, manned casualty rates. Experiments were conducted using the ground risk model, and probability distributions representing appropriate ranges for UAS weights and population density values. As shown in the Results and Discussion section, depending on the circumstances and failure rates used, the safety results were anywhere from one to seven orders of magnitude better than manned, historical rates.

Finally, looking at the hypothesis from 2.b in reverse, it was hypothesized that mandating TLS values more stringent than the current, overall casualty rate from manned aircraft would significantly reduce the potential combinations of UAS types and operating conditions. The results for this experiment were highlighted in Figure 78. The most important result of this experiment was demonstrated by the fact that simply changing the TLS value from 1×10^{-5} to 1×10^{-6} reduced the allowable experimental cases from 81% to 44%.

Research Contributions

As with any effort of this type, it is important to identify what specific contributions to the field that this effort will accomplish. Conversely, it is critical to review what the thesis was not intended to achieve. In the latter category, this research is certainly not designed to either identify or recommend specific integration methods. In other words, it does not endorse specific technology to assist in UAS integration or recommend any integration procedures. In addition, this thesis was not intended to specifically endorse the integration of certain categories of UAS for operation in any particular airspace or over particular population centers.

This thesis does make contributions in several areas related to UAS integration, however. These areas include an expanded analysis of third-party risk, analysis of the risk posed by lost link conditions, an examination of the impact of choosing TLS, and an overall framework to support UAS integration stakeholders.

One of the primary contributions this thesis makes is in the area of understanding the risk to third-party individuals due to UAS accidents that result in ground impact. Perhaps the most important aspect of this area is that the research validates the casualty prediction model proposed by using manned aircraft failure and casualty data. This is an extremely important step toward establishing a credible prediction tool.

Looking beyond validation, one can focus on the specific details of the casualty prediction tool. For example, previous studies did not take the behavioral patterns of people on the ground into account when examining population densities and the probability of causing casualties on the ground. Additionally, this research examines the size of the impact on the ground based on previous studies on aircraft crashes and adds a comparison of the impact area predictions using several aircraft accident reports. This research also includes more detailed data on the shelter provided by various structures and takes that level of shelter into account when predicting bystander casualties. The model also takes an energy-based approach to shelter effects but includes both the kinetic energy of the vehicle and the chemical energy of the fuel carried on the air vehicle.

This thesis also accounts for the risk posed by UAS lost link conditions. Using the event tree format, lost link conditions are included in the risk to other aircraft and to people on the ground. This contribution serves as a link between the ground risk and air risk and also allows the user of the model to help determine the minimum required link standards to achieve a desired level of safety. Without this step included in the model, an important aspect of UAS integration is not accounted for. Because of the exploration of the lost link model, a few things were discovered. The first is the importance of the interplay between the link failure rate and the MTTR or amount of time spent in a lost link condition. The Pareto front in Figure 91 demonstrated this principle. Second was the fact that lost link casualties were predicted to be fairly low, usually one order of magnitude lower than the corresponding ground or air casualties. As a result, tradeoffs involving lost link behavior may have to focus more on factors other than casualties such as disruption to the airspace and cost. Finally, the difference in casualty rates for an air-based and ground-based SAA system were demonstrated to be significant when compared only to casualties caused by lost link conditions (Table 57), but would still be minimal when compared to all casualties. Again, the tradeoffs for this decision would most likely based on other factors such as weight, cost and effectiveness.

The contributions outlined help combine to form the next contribution which is closing the gap in the literature review as depicted in Figure 12 on page 53. It is this gap, which allows stakeholders to more realistically determine the actual risk caused by UAS integration, which is also preventing a full understanding of that risk currently. Closing this gap by analyzing the risk that UAS pose to their environment in terms of air to air and ground risk will allow stakeholders to impose a safety goal and then work backward to establish system-level reliability goals for UAS.

In the air risk collision model, this thesis includes data from studies on both visual avoidance of other aircraft as well as electronic means of avoidance to populate the probability of avoiding a MAC. In addition, data on aircraft passenger and load factor numbers are included in the casualty prediction method. This model also incorporates different types of controlled airspace into the model as well as using realistic rates from actual airspace data to divide traffic into visual and instrument flight rules.

Another contribution is the discussion on the appropriate safety target for UAS integration and the quantitative analysis of the impact of that decision on UAS reliability. To date, the studies on UAS integration that have addressed a safety target or risk target have primarily used one target level and attempted to determine the impact of that one level. However, this thesis showed how choosing a safety target will affect choices about system reliability on the UAS and what those impacts are.

Finally, this thesis demonstrated an overall framework for the UAS integration process by applying the casualty prediction tool in Phase 3 of the approach. The framework, with the associated tools such as the Event Tree analysis, is important for this problem for two reasons. One, this problem is complex, multi-faceted, and involves a system of systems. As a result, it is difficult to analyze the problem integrally. Instead, many entities are looking at this problem now from different aspects without analyzing the problem holistically.

Second, the framework and tools espoused in this research are simple enough to support rapid analysis but can be adapted to include the results of more sophisticated modeling and simulation efforts. Therefore, the framework provides flexibility and the ability to vary levels of fidelity during the integration process. Ultimately, the framework is a description of the concept, process, and format of a way to predict UAS casualties and support UAS integration by aiding decision-makers and facilitating such steps as certification and developing system requirements.

FUTURE WORK

The challenge of integrating UAS into the NAS will still require much work in the years ahead. Stakeholders have a clear choice with respect to how to set requirements and certify the airworthiness of existing and new systems. The three major approaches are to use existing standards and regulations from manned aircraft and apply them to UAS, develop completely new standards and regulations for UAS, or some combination of the two.

This thesis has shown the disadvantages of trying to hold UAS to the same standards as manned aircraft. Although Haddon and Whittaker [81] discuss the cost benefits of using established codes and requirements, the additional requirements on reliability that this would unnecessarily place on UAS developers can not likely be justified. Even if regulators desired to use manned standards for UAS, there are some aspects of UAS that do not apply to manned aircraft and would require additional standards and regulation. As a result, regardless of whether the second or third approach above is selected, there will be a need for some new requirements. When developing these requirements, it clearly makes sense that they are linked to safety. To do so, however requires additional information to continually close the knowledge gap and better predict the risk posed by UAS.

As discussed in the Literature Review section and with respect to the Environmental Impact Assessment concept in Figure 15 in particular, one of the purposes of research of this nature is to drive future questions and exploration. An effort such as this is the first step on that knowledge spiral. Each new round of exploration generates new questions and drives the next round of questions. As a result of this research, listed below are several areas that require further research to better bridge the gap in knowledge. In fact, some of the knowledge areas listed below could be addressed at one or more of the six proposed UAS test centers.

First and foremost, in order to move forward on this problem, the stakeholders need an honest and open dialogue on what the desired safety goals for UAS are, if this approach is taken. An agreement is first needed on whether fatality rates are the metric of choice for this problem. This research used several proposed TLS levels, based typically on historical safety rates. However, if an official rate was presented by the FAA or another regulatory body then those who analyze this problem in the future could begin to use those rates in future studies similar to this one.

Next, the community needs a better understanding of the impact or exposure area caused by a UAS ground collision. This thesis paid particular attention to that aspect of UAS risk, but there needs to be additional research, especially on the impact area created by smaller UAS in built-up areas. This scenario is not only one of the more likely near-term uses of UAS due to the law enforcement mission, but potentially the most dangerous due to the higher population density values in urban areas.

Further research is also needed on the effects a UAS impact will have on people inside different types of shelter to include residential and commercial structures. This parameter also had a large impact on the ground casualty rates from the model. Every attempt was made in this effort to use realistic data from sources such as NASA and the DoD related to damage to buildings, but more can and should be done to better quantify this risk. This gap in information is particularly vital to understand for more complex high-rise style buildings more prevalent in urban areas. It has been demonstrated that there are urban areas that may be deemed unsafe for UAS operations, based on current reliability levels. However, a better understanding of the effects a fallen UAS would have on the occupants of a multi-story building is critical to fully modeling the risks UAS pose in urban areas.

Based on the relatively low cost of testing for both of these areas, and the potentially high cost of liability; virtual and actual testing of UAS crashes can and should be done to gain valuable insight into this area. It is not beyond the realm of possibility for researchers, government entities, and UAS manufacturers to combine resources to conduct realistic testing using UAS airframes and actual structures to better understand the risk associated with UAS crashes.

Another area of interest is the ability of human pilots aboard manned aircraft to visually identify UAS smaller than typical manned aircraft. The data used for visual detection and avoidance in this research were based on experiments conducted between manned aircraft. There needs to be additional research on the probability of visually acquiring and potentially avoiding a collision with an air vehicle that could potentially be much smaller than even the smallest GA or experimental aircraft.

Studies should also be conducted on the proper behavior of an air vehicle in the event of a lost link. This research has demonstrated that the casualty rates for lost link events are typically one order of magnitude lower than the casualty rates due to system failures or even midair collisions. As a result, there needs to be additional exploration of the tradeoffs between casualties on the ground due to a lost link and the disruption caused by UAS trying to execute preprogrammed instructions to seek a designated safe area.

While Sense and Avoid has gained much attention in this problem, the idea of an effectiveness rate should be incorporated into these efforts. The model created for this thesis can differentiate between SAA that is ground-based or air-based in terms of the logic used to determine whether it is effective in a lost link condition, as demonstrated in the previous section. This differentiation can help determine tradeoffs between the two types of systems and also drive the requirements in terms of the reliability and effectiveness of anything in development. It is not possible to develop and discuss performance standards for SAA without first understanding the required effectiveness of such as system. For example, the experiment conducted to populate Table 55 demonstrates that a Group 3 UAS operating in Class B airspace would require a SAA system that is 90.8% effective in avoiding midair collisions, given an encounter. System developers could use that information, combined with known traffic density, relative airspeeds, and the flight characteristics of known aircraft and UAS to develop applicable performance standards for the SAA system.

This research did not specifically address UAS operator training, but this area has been identified as a potential integration challenge. However, it is possible to include the impact of a lack of proper training into the analysis inherent in this framework. Human error can be used as one more contributor to the system failure rate. With a known UAS and corresponding system failure rate due to hardware, the maximum failure rate attributable to human error could be derived from the TLS framework. As a result of this analysis, training and operator requirements can be driven by that rate, similar to how systems would be designed with a maximum equipment failure rate as a goal.

Overall, UAS integration is both an exciting opportunity for the aerospace community and a daunting challenge to those responsible for ensuring the safety of the NAS the public. This problem has both technical and operational challenges as well as regulatory and standards challenges. In addition, there is a growing concern from the public, at the time of writing this document, about privacy. If not handled correctly, the process of integrating UAS could cause tremendous public backlash. While the issue of privacy is a much more political and legal concern, safety is clearly a concern for the regulators and stakeholders directly involved in this process. It is crucial to ensure that any efforts to integrate UAS be done with a clear understanding of the safety implications involved. Just as no one in the present time would consider dumping chemicals in a river without first studying the impact to the environment, allowing UAS to enter the NAS should be done with the same understanding of the impact to the 'environment' made possible by the research presented in an effort such as this one.

REFERENCES

1. *National Aeronautics Research and Development Plan*, Office of the President of the United States, Editor. 2010: Washington, DC.
2. Krock, L. *Timeline of UAVs*. Spies That Fly 2002 [cited 2011 March 21]; Available from: http://www.pbs.org/wgbh/nova/spiesfly/uavs.html.
3. Garamone, J. (2002) *From U.S. Civil War to Afghanistan: A Short History of UAVs*. American Forces Press Service.
4. *Unmanned Aircraft Systems Roadmap 2005-2030*, Office of the Secretary of Defense, Editor. 2005: Washington, D.C.
5. *Vision 100 - Century of Aviation Reauthorization Act*. 2003: Washington, DC.
6. Cropsey, L., *Integrating Military Unmanned Aircraft into the National Airspace System: An Application of Value-Focused Thinking and Enterprise Architecting*, in *System Design and Management*. 2008, Massachusetts Institute of Technology.
7. RTCA. *RTCA, Inc.* [Website] 2011 [cited 2012; Available from: http://www.rtca.org/aboutrtca.asp.
8. (2012) *UAS Global Airspace Integration, RTCA Special Committee 203*.
9. *Department of Defense Final Report to Congress on Access to National Airspace for Unmanned Aircraft Systems*, Department of Defense, Editor. 2010: Washington, DC.
10. Joint Planning and Development Office, *NextGen UAS Research, Development and Demonstration Roadmap*. 2012.

11. Federal Aviation Administration. *FAA Makes Progress with UAS Integration*. 2012 [cited 2012 May 14]; Available from: http://www.faa.gov/news/updates/?newsId=68004.
12. *FAA Modernization and Reform Act of 2012*. 2012: Washington, D.C.
13. Brewin, B. (2012) *FAA Delays Creating Drone Test Sites Due to Privacy Concerns*. NextGov.
14. *Unmanned Aircraft System Airspace Integration Plan*, Department of Defense, Editor. 2011.
15. Wikipedia. *Unmanned Aerial Vehicle*. [cited 2012 June 21]; Available from: http://en.wikipedia.org/wiki/Unmanned_aerial_vehicle.
16. Federal Aviation Administration, *Unmanned Aircraft Operations in the National Airspace System*, Department of Transportation, Editor. 2006: Washington D.C.
17. Federal Aviation Administration, *Model Aircraft Operating Standards*, Department of Transportation, Editor. 1981: Washington, D.C.
18. *Regulation No 1592/2002 of the European Parliament and of the Council on Common Rules in the Field of Civil Aviation and Establishing a European Aviation Safety Agency*. 2002.
19. Blyenburgh, P.V. (2010) *Overview of the European UAS Community*. 2010-2011 UAS Yearbook - UAS: The Global Perspective.
20. *Federal Aviation Regulations*,. Electronic Code of Federal Regulations 2010 [cited 2011; Available from: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&tpl=/ecfrbrowse/Title14/14tab_02.tpl.

21. Smith, D.D.J., *Reliability, Maintainability and Risk*. 6th ed. 2001, Oxford, Great Britain: Butterworth Heinemann.

22. SAE International, *Guidelines and Methods for Conducting the Safety Assessment PRocess on Civil Airborne Systems and Equipment*. 1996: Warrendale, PA.

23. Stamatelatos, M., et al., *Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners.* 2011.

24. Department of Defense, *Risk Management Guide for DoD Acquisition*. 2006.

25. Federal Aviation Administration, *AFS Safety Assurance System (SAS) Overview Glossary and Acronym List*. 2012.

26. Federal Aviation Administration, *Safety Management System Guidance*, Department of Transportation, Editor. 2008: Washington, D.C.

27. Range Commanders Council, *Common Risk Criteria Standards for National Test Ranges*. 2007, Range Safety Group: White Sands Missile Range.

28. Federal Aviation Administration (2012) *COA Sponsor List*.

29. Federal Aviation Administration. *Certificate of Authorization or Waiver*. 2012 [cited 2012 June 21]; Available from: http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/systemops/aaim/organizations/uas/coa/.

30. Department of Defense, *Unmanned Systems Integrated Roadmap FY 2011-2036*, T.L. Office of the Undersecretary of Defense for Acquisition, Editor. 2011: Washington, D.C.

31. Rango, A. and A.S. Laliberte, *Impact of Flight Regulations on Effective Use of Unmanned Aircraft Systems for Natural Resources Applications.* Journal of Applied Remote Sensing, 2010. **4**(043539).

32. Federal Aviation Administration, *Airworthiness Certification of Unmanned Aircraft Systems*, Department of Transportation, Editor. 2008: Washington D.C.

33. Federal Aviation Administration, *Interim Operational Approval Guidance 08-01*, Aviation Safety Unmanned Aircraft Program Office, Editor. 2008: Washington, DC.

34. SAE International, *Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airbore Systems and Equipment*. 1996.

35. SAE International, *Certification Considerations for Highly-Integrated or Complex Aircraft Systems*. 1996: Warrendale, PA.

36. *Equivalent Level Of Safety*. [cited 2012 June 27]; Available from: http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgELOS.nsf/MainFrame?OpenFrameSet.

37. Cuerno-Rejado, C., R. Martinez-Val, and E. Garcia-Julia, *Integration of UAS in the Civil Airworthiness Regulatory System: Present and Future*, in *25th Bristol International UAV Systems Conference*.

38. Range Commanders Council, *Range Safety Criteria for Unmanned Air Vehicles*. 1999: White Sands Missile Range.

39. Range Commanders Council, *Range Safety Criteria for Unmanned Air Vehicles Rationale and Methodology Supplement*. 2001, Range Safety Group: White Sands Missile Range.

40. *Risk Assessment: A Survey of Characteristics, Applications and Methods Used by Federal Agencies for Engineered Systems*, Federal Coordinating Council for Science Engineering and Technology, Editor. 1992.

41. NATO Standardization Agency, *STANAG 4671 Unmanned Aerial Vehicles Systems Airworthiness Requirements (USAR)*. 2009: Brussels, Belgium.

42. Civil Aviation Safety Authority Australia, *AC 101-1 Unmanned Aerial Vehicle (UAV) Operations, Design Specification, Maintenance and Training of Human Resrouces*. 2002.

43. Australian Aerospace Industry Forum, *AAIF Review of Draft CASA Advisory Materials*, AAIF Certification and Regulation Working Group Unmanned Aircraft Systems Sub-Committee,.

44. International Civil Aviation Organization (ICAO), *Circular 328, Unmanned Aircraft Systems (UAS)*. 2011: Montreal, Quebec, Canada.

45. Allouche, M., *UAS Airworthiness Certification & System Safety Requirements Outstanding Issues and Recommendations*, in *EC UAS Panel Third Workshop*. 2011.

46. *Policy Statement Airworthiness Certification of Unmanned Aircraft Systems (UAS)*. 2009, European Aviation Safety Agency,.

47. Civil Aviation Authority Israel, *CAAI UAV Systems Airworthiness Regulations*.

48. Civil Aviation Authority (UK), *Unmanned Aircraft System Operations in UK Airspace – Guidance*, S.R. Group, Editor. 2012.

49. Monmouth University (2012) *U.S. Supports Some Domestic Drone Use*.

50. DeGarmo, M.T., *Issues Concerning Integration of Unmanned Aerial Vehicles in Civil Airspace*. 2004, Mitre: McLean, VA.

51. *Teal Group Predicts Worldwode UAV Market Will Total $89 Billion in Its 2012 UAV Market Profile and Forecast*. 2012 April 11, 2012 [cited 2012 October 3]; Available from: http://tealgroup.com/index.php/about-teal/teal-group-in-the-media/3/79-teal-group-predicts-worldwide-uav-market-will-total-89-billion-in-its-2012-uav-market-profile-and-forecast.

52. Roston, A. (2012) *GAO: 76 Nations Have UAVs*. Defense News.

53. Bergen, P. (2012) *A Dangerous New World of Drones*.

54. Association for Unmanned Vehicles Systems International, *Unmanned Aircraft System Integration into the United States National Airspace System: An Assessment of the Impact on Job Creation in the U.S. Aerospace Industry*. 2010. p. 20.

55. Hayhurst, K., *Certification*, NASA, Editor. 2010, Meeting of Experts on NASA's Unmanned Aircraft Systems in the National Airspace Systems (NAS) Project.

56. *ADVANCE -NOTICE OF PROPOSED AMENDMENT (NPA) No 16/2005 Policy for Unmanned Aerial Vehicle (UAV) certification.*, European Aviation Safety Agency, Editor.

57. *Sense and Avoid (SAA) for Unmanned Aircraft Systems (UAS)*, Federal Aviation Administration, Editor. 2009, FAA Sense and Avoid Workshop.

58. Williams, J., *Phonecon*. 2010: Atlanta.

59. *Aircraft Owners and Pilots Association*. 2010 [cited 2010 October 20]; Available from: http://www.aopa.org/whatsnew/regulatory/unmanned.html.

60. *National Aeronautics Research and Development Plan*. 2010; 56]. Available from: http://www.whitehouse.gov/administration/eop/ostp/nstc/aero.

61. Kalinowski, N. and J. Allen, *Joint Statement of Nancy Kalinowski, Vice President, System Operations Services, Air Traffic Organization, and John Allen, Director, Flight Standards Service, Aviation Safety, Federal Aviation Administration, Before the House of Representatives, Committee on Homeland Security, Subcomittee on Border, Maritime, and Global Counterterrorism, on the Role of Unmanned Aerial Systems of Border Security, July 15, 2010*, Federal Aviation Administration, Editor. 2010: Washington, DC.

62. Ahern, D.G., *Testimony Of David G. Ahern Director, Portfolio Systems Acquisition Office Of The Under Secretary Of Defense (Acquisition, Technology & Logistics) Before The United States Senate Committee On Commerce, Science And Transportation Subcommittee On Aviation Operations, Safety And Security*. 2010: Washington, DC.

63. Rice, L.S., *Statement By Brigadier General L. Scott Rice Before The Senate Commerce Committee Subcommittee On Aviation Operations, Safety, And Security Second Session, 111th Congress On The Integration Of Unmanned Aircraft Systems Into The National Airspace System: Fulfilling Imminent Operational And Training Requirements*, Air National Guard, Editor. 2010: Washington, DC.

64. *Minimum Aviation System Performance Standards For Automatic Dependent Surveilance Broadcast (ADS-B)*. 2002, RTCA: Washington, D.C.,.

65. Association for Unmanned Vehicles Systems International, *Unmanned Aircraft System Operations Industry "Code of Conduct"*, in *AUVSI Website*. 2012.

66. Nathan, S. (2012) *Roundtable: Development of Civilian UAVs*. The Engineer.

67. Saglimbene, M.S. *Reliability Analysis Techniques: How They Relate To Aircraft Certification*. in *Reliability and Maintainability Symposium*. 2009. Fort Worth, TX.

68. Federal Aviation Administration, *Reliability, Maintainability and Availability (RMA) Handbook*. 2008.

69. Saglimbene, M.S. *Reliability Analysis Techniques: How they Relate to Aircraft Certification*. 2009: IEEE.

70. Ale, B.J.M., et al., *Towards a Causal Model for Air Transport Safety- an Ongoing Research Project.* Safety Science, 2006. **44**: p. 17.

71. TCAS on UAS Team Unmanned Aircraft Program Office, *Evaluation of Candidate Functions for Traffic Alert and Collision Avoidance System II on Unmanned Aircraft Systems*, F.A. Administration, Editor. 2011, Flight Standards Service: Washington, D.C.

72. *System Safety Analysis and Assessment for Part 23 Airplanes*, Department of Transportation, Editor. 2009.

73. *System Design and Analysis*, Department of Transportation, Editor. 1988.

74. *Certification Specifications for Large Aeroplanes CS-25*, European Aviation Safety Agency, Editor. 2009.

75. *Common Risk Criteria for National Test Ranges: Inert Debris*. 2002, Range Commanders Council: White Sands Missile Range, NM. p. 20.

76. *Expected Casualty Calculations For Commercial Space Launch and Reentry Missions*, Department of Transportation, Editor. 2000.

77. *Safety Goals for the Operations of Nuclear Power Plants: Policy Statement*, Nuclear Regulatory Commission, Editor. 1986.

78. Organization for Economic Cooperation and Development, *The Structure and Application of High-Level Safety Goals*. 2011, Nuclear Energy Agency.

79. Roelen, A.L.C., et al., *A Causal Model for the Assessment of Third Party Risk Around Airports*. 2000, Ministry of Transport.

80. Backman, M.E., *Terminal Ballistics*. 1976, Naval Weapons Center: China Lake, California.

81. Haddon, D.R. and C.J. Whitaker, *Aircraft Airworthiness Certification Standards for Civil UAVs*, C.A. Authority, Editor. 2002: United Kingdom. p. 1-15.

82. *Federal Aviation Regulations*. [Electronic Regulations] 2010 September 15, 2010; Available from: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=9d59c8da3b10a68dbd1edb2de284eb8f&rgn=div8&view=text&node=14:1.0.1.1.1.0.1.2&idno=14>

83. *Equivalent Levels of Safety*. [cited 2011 February 15]; Federal Aviation Administration Regulation and Guidance Library Website]. Available from: http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgELOS.nsf/MainFrame?OpenFrameSet.

84. *Using Unmanned Aerial Systems Within the Homeland: Security Game Changer?*, in *House Committee on Homeland Security*. 2012.

85. Federal Aviation Administration and Eurocontrol, *A Concept Paper for Separation Safety Modeling*. 1998.

86. Leveson, N.G., *Engineering a Safer World*, in *Systems Thinking Applied to Safety*. 2009, Massachusetts Institute of Technology Press.

87. Gibson, S.B., *Major Hazards - Should They be Prevented at All Costs?* Engineering and Process Economics, 1978. **3**: p. 9.

88. Clothier, R., et al., *Definition of an Airworthiness Certification Framework for Civil Unmanned Aircraft Systems.* Safety Science, 2011.

89. Evans, A.W., et al., *Third Party Risk Near Airports and Public Safety Zone Policy*. 1997: London, England.

90. Waggoner, B., *Developing a Risk Assessment Tool for Unmanned Aircraft System Operations*, in *Department of Aeronautics and Astronautics*. 2010, University of Washington.

91. Weibel, R.E. and R.J. Hansman, *Safety Considerations for Operation of Unmanned Aerial Vehicles in the National Airspace System*. 2005, MIT International Center for Air Transportation: Cambridge, MA.

92. Clothier, R., et al., *A Casualty Risk Analysis for Unmanned Aerial System (UAS) Operations Over Inhabited Areas*, in *AIAC12- Twelfth Australian International Aerospace Congress*. 2006.

93. Burke, D.A., *System Level Airworthiness Tool: A Comprehensive Approach to Small Unmanned Aircraft System Airworthiness*, in *Aerospace Engineering*. 2010, North Carolina State University.

94. Clothier, R., et al. *A Casualty Risk Analysis for Unmanned Aerial System (UAS) Operations Over Inhabited Areas*. 2007: Citeseer.

95. Dalamagkidis, K., K.P. Valavanis, and L.A. Piegl, *Evaluating the Risk of Unmanned Aircraft Ground Impacts*, in *16th Mediterranean Conference on Control and Automation*. 2008: Ajaccio, France.

96. Ale, B. and M. Piers, *The Assessment and Management of Third Party Risk Around a Major Airport.* Journal of Hazardous Materials, 2000. **71**(1-3): p. 1-16.

97. Thompson, K.M., R.F. Rabouw, and R.M. Cooke, *The Risk of Groundling Fatalities from Unintentional Airplane Crashes.* Risk Analysis, 2001. **21**(6): p. 13.

98. Netjasov, F. and M. Janic, *A Review of the Research on Risk and Safety Modelling in Civil Aviation*, in *Third International Conference on Research in Air Transportation*. 2008: Fairfax, VA. p. 169-176.

99. Federal Aviation Administration. *NextGEN*. 2012 June 18, 2012]; Available from: http://www.faa.gov/nextgen/.

100. *NextGen Implementation Plan*. 2010 [cited 2010 September 28]; Available from: http://www.faa.gov/about/initiatives/nextgen/media/appendix_b.pdf.

101. Kochenderfer, M.J., et al., *Airspace Encounter Models for Estimating Collision Risk.* Journal of Guidance, Control, and Dynamics, 2010. **33**(2): p. 487-499.

102. Kochenderfer, M.J., et al., *Uncorrelated Encounter Model of the National Airspace System*. 2008, MIT Lincoln Laboratory: Cambridge, MA.

103. Taneja, N. and D.A. Wiegmann. *Analysis of Mid-Air Collisions in Civil Aviation*. in *45th Annual Meeting of the Human Factors and Ergonomics Society*. 2001. Santa Monica, CA.

104. Brooker, P., *Airborne Separation Assurance Systems: Towards a Work Programme to Prove Safety*, in *Safety Science*. 2004, Cranfield University: Bedfordshire, England. p. 723-754.

105. *Guide to Reusable Launch and Reentry Vehicle Reliability Analysis*. 2005, Federal Aviation Administration,: Washington, D.C.

106. Federal Aviation Administration, *Expected Casualty Calculations for Commercial Space Launch and Reentry Missions*, U.S. Department of Transportation, Editor. 2000: Washington, D.C.

107. Cole, J.K., L.W. Young, and T. Jordan-Culler, *Hazards of Falling Debris to People, Aircraft, and Watercraft*. 1997, Sandia National Laboratories: Albuquerque, NM.

108. Lin, M.Y.Y., E.W.F. Larson, and J.D. Collins, *Determination of Debris Risk to the Public Due to the Columbia Breakup During Reentry*. 2003, Valador.

109. Cole, J.K. and W.P. Wolfe, *Hazards to People and Aircraft from Flight Test Debris Generated at High Altitudes*, in *34th AIAA Aerospace Sciences Meeting and Exhibit*. 1996: Reno, NV.

110. Gonzales, E.A.Z. and D.P. Murray, *The FAA's Approach to Ground and NAS Separation Distances for Commercial Rocket Launches*, in *48th AIAA Aerospace Sciences Meeting*. 2010: Orlando, FL.

111. Department of Defense, *DoD Ammunition and Explosives Safety Standards*. 2008, Office of the Deputy Under Secretary of Defense (Installations and Environment): Washington, D.C.

112. Chipley, M., et al., *Reference Manual to Mitigate Potential Terrorist Attacks Against Buildings,* Federal Emergency Management Agency, Editor. 2003.

113. National Aerospace Laboratory, *Aviation Safety Targets for Effective Regulation*. 2010, The European Commission. p. 89.

114. Dalamagkidis, K., K.P. Valavanis, and L.A. Piegl, *On Integrating Unmanned Aircraft Systems into the National Airspace System: Issues, Challenges, Operational Restrictions, Certification, and Recommendations*. Vol. 36. 2008: Springer Verlag.

115. Weibel, R.E. and R.J.H. Jr., *An Integrated Approach to Evaluating Risk Mitigation Measures for UAV Operational Concepts in the NAS*, in *AIAA 2005*. 2005: Arlington, VA.

116. Jonkman, S.N., *Loss of Life Estimation in Flood Risk Assessment.* Delft: Delft University of Technology, 2007.

117. Coburm, A., R. Spence, and A. Pomonis. *Factors Determining Human Casualty Levels in Earthquakes: Mortality Prediction in Building Collapse*. 1992.

118. Deelstra, Y., et al., *Using Knowledge for Decision-making Purposes in the Context of Large Projects in The Netherlands.* Environmental Impact Assessment Review, 2003. **23**(5): p. 517-541.

119. Wathern, P., *Environmental Impact Assessment: Theory and Practice*. 1990: Psychology Press.

120. Dezfuli, H., *Safety and Reliability Analysis Presentation*, Advanced Planning and Integration Office, Editor, National Air and Space Agency,.

121. Federal Aviation Administration, *Automatic Dependent Surveillance Broadcast (ADS-B) Out Performance Requirements to Support Air Traffic Control (ATC) Service*, D.o. Transportation, Editor. 2010, Federal Register: Washington, DC.

122. Lacher, A.R., D.R. Maroney, and D.A.D. Zeitlin, *Unmanned Aircraft Collision Avoidance - Technology Assessment and Evaluation Methods*. 2007, The MITRE Corporation: McLean, VA.

123. MITRE Corporation, *System Safety Study of Minimum TCAS II* 1983: McLean, VA. p. 376.

124. Cirrus Owners and Pilots Association. *Cirrus Airframe Parachute System Deployment History*. 2012 January 10, 2012 [cited 2012 May 4]; Available from: http://www.cirruspilots.org/Content/CAPSHistory.aspx.

125. Schallhorn, S., et al., *Visual Search in Air Combat*. 1990, DTIC Document.

126. Costanza, E.B., R.S. Scott, and H.L. Snyder, *Air to Air Target Acquisition: Factors and Means of Improvement*. 1980, Virginia Polytechnic Institute and State University: Blacksburg, VA.

127. Graham, W., *See and Avoid/Cockpit Visibility*. 1989, DTIC Document.

128. Jonkman, S., P. Van Gelder, and J. Vrijling, *An Overview of Quantitative Risk Measures for Loss of Life and Economic Damage.* Journal of Hazardous Materials, 2003. **99**(1): p. 1-30.

129. Scuffham, P., et al. (2002) *Direct and Indirect Cost of General Aviation Crashes*. Aviation, Space, and Environmental Medicine **73**, 851-858.

130. Federal Aviation Administration, *Treatment of the Value of Preventing Fatalities and Injuries in Preparing Economic Analyses*.

131. Levy, S. (2012) *NASA, UND, MITRE Team Up for Unmanned Sense-and-Avoid Testing*. Association for Unmanned Vehicle Systems International News, .

132. Andrews, J.D. and S.J. Dunnett, *Event-tree Analysis Using Binary Decision Diagrams.* Reliability, IEEE Transactions on, 2000. **49**(2): p. 230-238.

133. Geisinger, K., *Guide to Methods & Tools for Safety Analysis in Air Traffic Management*, G.W.G. B, Editor. 2003, Global Aviation Information Network.

134. Blom, H., et al. *Stochastic Analysis Background of Accident Risk Assessment for Air Traffic Management*. 2003.

135. *Worldwide UAV Roundup*. [cited 2011 February 3]; Available from: http://www.aerospaceamerica.org/Documents/March%202011%20AA%20PDFs/UAV_CHART_2011.pdf.

136. *Wikipedia*. [cited 2012; Available from: www.wikipedia.com.

137. *FY2009-2034 Unmanned Systems Integrated Roadmap*. 2009, Department of Defense: Washington, D.C.

138. Long, E.A., et al., *Empirical Relationships Between Reliability Investments and Life-Cycle Support CostsTS*. 2007, LMI Government Consulting.

139. *ADS-B Out Performance Requirements to Support Air Traffic Control (ATC) Service: Final Rule* Federal Aviation Administration, Editor. 2010.

140. Weibel, R.E., M. Edwards, and C. Fernandes, *Establishing a Risk-Based Separation Standard for Unmanned Aircraf Self Separation*, in *Ninth Europe/USA*

Air Traffic Management Research and Development Seminar. 2011: Berlin, Germany.

141. May, G., *A Method for Predicting the Number of Near Mid-Air Collisions in a Defined Airspace.* Operational Research Quarterly, 1971. **22**(3): p. 237-251.

142. Kochenderfer, M.J., et al., *A Comprehensive Aircraft Encounter Model of the National Airpsace System.* Lincoln Laboratory Journal, 2008. **17**(2): p. 41-53.

143. *Load Factor: All Carriers All Airports*, Bureau of Transportation Statistics, Editor. 2012: Washington, D.C.

144. *Risk Factors Associated with Weather-Related General Aviation Accidents*. 2005, National Transportation Safety Board: Washington, D.C.

145. *Weather-Related Aviation Accident Study 2003-2007*. 2010, Federal Aviation Administration,.

146. Asim, M., D.N. Ehsan, and K. Rafique. *Probable Causal Factors in UAV Accidents Based on Human Factor Analysis and Classification System*. in *27th International Congress of the Aeronautical Sciences*. 2010.

147. U.S. Census Bureau. *Population Density of the United States*. [cited 2011; Available from: http://www.census.gov/population/www/censusdata/2000maps.html.

148. Klepeis, N.E., et al., *The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants.* Journal of Exposure Analysis and Environmental Epidemiology, 2001. **11**(3): p. 231-252.

149. *Columbia Accident Investigation Board Report*. 2003: Washington, D.C.

150. Freitas, P.J., *Passenger Aviation Security, Risk Management, and Simple Physics.* Journal of Transportation Security, 2012: p. 1-16.

151. Explosives Safety Board, *Approved Methods and Algorithms for DOD Risk-Based Explosives Siting*. 2007: Alexandria, VA.

152. Binder, K., *Monte-Carlo Methods*, in *Mathematical Tools for Physicists*, G. Trigg, Editor. 2005, Wiley-VCH: Mainz, Germany.

153. *Guide to Using @Risk*, in *Risk Analysis and Simulation Add-In for Microsoft Excel*. 2010, Palisade Corporation: Ithaca, NY.

154. Matsumoto, M. and T. Nishimura, *Mersenne Twister: a 623-dimensionally Equidistributed Uniform Pseudo-Random Number Generator.* ACM Transactions on Modeling and Computer Simulation (TOMACS), 1998. **8**(1): p. 3-30.

155. *Systems Engineering Fundamentals*. 2001, Defense Acquisition University Press: Fort Belvoir, VA.

156. Barlas, Y., *Formal Aspects of Model Validity and Validation in System Dynamics.* System dynamics review, 1996. **12**(3): p. 183-210.

157. *Google Images*. [cited 2012; Available from: http://www.google.com/imghp?hl=en&tab=wi.

158. Clothier, R.A., et al. *Definition of airworthiness categories for civil Unmanned Aircraft Systems (UAS)*. 2010.

159. Baker, S. and G. Li, *Crash Risk in General Aviation.* Journal of the American Medical Association, 2007. **297**(14): p. 3.

160. Dell'Acqua, F. and P. Gamba, *Texture-based Characterization of Urban Environments on Satellite SAR Images.* IEEE Transactions on Geoscience and Remote Sensing, 2003. **41**(1): p. 153-159.

161. Lum, C., et al., *Assessing and Estimating Risk of Operating Unmanned Aerial Systems in Populated Areas.* American Institute of Aeronautics and Astronautics: p. 14.

162. Solomon, K.A. (1988) *Analysis of Ground Hazards due to Aircrafts and Missiles*.

163. Department of Energy, *Accident Analysis For Aircraft Crash Into Hazardous Facilities*. 2006: Washington, D.C.

164. Brady, S.D., R.J. Hillestad, and R. Corporation, *Modeling the external risks of airports for policy analysis*. 1995: RAND Corporation.

165. *Uninhabited Aerial Vehicles and Uninhabited Combat Aerial Vehicles*, Defense Science Board, Editor. 2004: Washington, D.C.

166. National Transportation Safety Board, *Aircraft Accident Report, Cessna Citation 501, N15NY*. 1979: Washington, DC.

167. National Transportation Safety Board, *Aircraft Accident Report, Controlled Flight Into Terrain Korean Air Flight 801*. 1997: Washington, DC.

168. National Transportation Safety Board, *Aircraft Accident Brief, Learjet 35A*. 2006: Washington, DC.

169. National Transportation Safety Board, *Collision With Trees on Final Approach, Federal Express Flight 1478*. 2002: Washington, D.C.

170. Reed, W.H., et al., *Full-Scale Dynamic Crash Test of a Douglas DC-7 Aircraft*. 1965, Aviation Safety Engineering Reseach Division of Slight Safety Foundation: Phoenix, AZ.

171. National Transportation Safety Board, *Aircraft Accident Summary Report In-Flight Fire, Emergency Descent and Crash in a Residential Area Cessna 310R*. 2009: Washington, D.C.

172. National Transportation Safety Board, *Aircraft Accident Brief CASA C-212, N960BW*. 2006: Washington, D.C.

173. Pikaar, A.J., C.J.M. deJong, and J. Weijts, *An Enhanced Method for the Calculation of Third Party Risk Around Large Airports with application to Schiphol*. 2000, Dutch National Aerospace Laboratory (NLR).

174. National Transportation Safety Board, *U.S. Civil Aviation Accidents: Review of Aircraft Accident Data 2007-2009*. 2011: Washington, D.C.

175. Aircraft Owners and Pilots Association. *General Aviation Information and Statistics*. 2011 March 11, 2012]; Available from: http://www.aopa.org/whatsnew/stats/safety.html#gaaccidents.

176. Clothier, R.A. and R.A. Walker. *Determination and Evaluation of UAV Safety Objectives*. in *21st International Unmanned Aerial Vehicle Systems Conference*. 2006. Bristol, United Kingdom.

177. *ArcGIS Online*. 2012.

178. National Transportation Safety Board. *Table 10: Aviation Accidents, Fatalities and Rates, 1990 through 2009: U.S. General Aviation*. Available from: http://www.ntsb.gov/aviation/Table10.htm.

179. Office of Planning Environment and Realty. *Census 2000 Population Statistics*. [cited 2012 May 10]; Online Database]. Available from: http://www.fhwa.dot.gov/planning/census_issues/archives/metropolitan_planning/cps2k.cfm.

180. Hayter, A.J., *Probability and Statistics for Engineers and Scientists*. 2nd ed. 2002, Pacific Grove, CA: Duxbury.

181. National Transportation Safety Board, *Table 5: Accidents, Fatalities, and Rates, 1992 through 2011 for U.S. Air Carriers Operating Under 14 CFR 121*. 2011: Washington, DC.

182. National Transportation Safety Board, *Air Carrier Accident Data Used in Annual Review*. 1999.

183. Knecht, W.R. *Modeling the Big Sky Theory*. in *Human Factors and Ergonomics Society 45th Annual Meeting*. 2001. Santa Monica, CA.

184. Marks, B.L., *Air Traffic Control Separation Standards and Collision Risk*. 1963, Ministry of Aviation: London, England.

185. Alexander, B., *Aircraft Density and Midair Collision.* Proceedings of the IEEE, 1970. **58**(3): p. 377-381.

186. Endoh, S., *Aircraft Collision Models*. 1982, Massachusetts Institute of Technology.

187. Flanagan, P.D. and K.E. Willis, *Frequency of Air Space Conflicts in the Mixed Terminal Environment*. 1969.

188. Chang, E., et al., *The Story of Mode S.* Dec, 2000. **15**: p. 1-40.

189. Graham, W. and R.H. Orr (1970) *Terminal Air Traffic Flow and Collision Exposure*. Proceedings of the IEEE **58**, 9.

190. Richie, J.M., *Description of the Derivation of the Collision Risk Model Used in the Vertical Separation Simulation Risk Model*. 1989, Federal Aviation Administration Technical Center: Atlantic City, NJ.

191. Federal Aviation Administration, *NextGEN Implementation Plan*, Department of Transportation, Editor. 2012: Washington, D.C.

192. Krozel, J., et al. *Aggregate Statistics of the National Airspace System*. 2003.

193. Degen, S., *Reactive Image-based Collision Avoidance System for Unmanned Aircraft Systems*, in *Built Environment and Engineering*. 2011, Queensland University of Technology: Queensland, Australia.

194. Graham, W. and R.H. Orr, *Separation of Air Traffic by Visual Means: An Estimate of the Effectiveness of the See-and-Avoid Doctrine.* Proceedings of the IEEE, 1970. **58**(3): p. 26.

195. Morris, C.C., *Midair Collisions: Limitations of the See-and-avoid Concept in Civil Aviation.* Aviation, space, and environmental medicine, 2005. **76**(4): p. 357-365.

196. Dennis, N. and D. Lyle, *Bird Strike Damage & Windshield Bird Strike Final Report*, European Aviation Safety Agency.

197. Range Commanders Council, *Common Risk Criteria for National Test Ranges: Supplement*. 2007, Range Safety Group: White Sands Missile Range.

198. General Aviation Manufacturer's Association, *General Aviation Statistical Databook & Industry Outlook*. 2010: Washington, D.C.

199. Bureau of Transportation Statistics, *Air Carrier Profile*. 2009, Research and Innovative Technology Administration: Washington, D.C.

200. Federal Aviation Administration, *Administrator's Fact Book*, D.o. Transportation, Editor. 2011: Washington D.C.

201. Research and Innovative Technology Administration, *Table 2-9: Air Carrier Safety Data*. 2010, Bureau of Transportation Statistics,.

202. Research and Innovative Technology Administration, *Table 2-10: U.S. Commuter Air Carrier Safety Data*. 2011, Bureau of Transportation Statistics,.

203. Research and Innovative Technology Administration, *Table 2-13: U.S. On Demand Air Taxi Safety Data*. 2011, Bureau of Transportation Statistics,.

204. Research and Innovative Technology Administration, *Table 2-14: U.S. General Aviation Safety Data*. 2011, Bureau of Transportation Statistics,.

205. *See and Avoid*. Available from: http://seeandavoid.org/.

206. Research and Innovative Technology Administration, *Table 2-15: Number of Pilot-Reported Near Midair Collisions (NMAC) by Degree of Hazard*. 2010, Bureau of Transportation Statistics,.

207. Rose, K., et al., *Parameter Sensitivities, Monte Carlo Filtering, and Model Forecasting under Uncertainty*. Journal of Forecasting, 1991. **10**: p. 17.

208. Air Line Pilots Association International (2011) *Unmanned Aircraft Systems: Challenges for Safely Operating in the National Airspace System*.

209. Doerry, N. and D. Clayton. *Shipboard Electrical Power Quality of Service*. in *Electric Ship Technologies Symposium*. 2005.

210. Kendoul, F., *Towards a Unified Framework for UAS Autonomy and Technology Readiness Assessment (ATRA)*, in *International Conference on Intelligent Unmanned Systems*. 2011.

211. *Census of Fatal Occupational Injuries*. 2010, Bureau of Labor Statistics.

212. Sandquist, G. and R. Melnyk. *Analysis of Uncertainty in Modeling Perceived Risks*. in *ICONE 13: Nuclear Power-Meeting the Energy Challenge for the Environment*. 2005. Beijing, China.

213. National Highway Traffic Safety Administraion, *Fatality Analysis Reporting System*. 2009.

214. Forbes, J.A., et al., *Developing a Reliability Investment Model*. 2008, LMI.

215. National Transportation Safety Board, *Safety Study: Public Aircraft Safety*. 2001: Washington, D.C.

216. Centers for Disease Control and Prevention. *National Center for Health Statistics FastStats*. August 20, 2012 [cited 2012 September 7]; Available from: http://www.cdc.gov/nchs/fastats/acc-inj.htm.

217. Centers for Disease Control and Prevention. *Injury Prevention and Control: Data and Statistics (Wisqars)*. January 11, 2012 [cited 2012 September 7]; Available from: http://www.cdc.gov/injury/wisqars/fatal_injury_reports.html.

218. U.S. Department of Labor. *OSHA Quick Takes*. 2012 [cited 2012 September 7]; Available from: http://www.osha.gov/oshstats/commonstats.html.

219. U.S. Customs and Border Protection (2011) *Unmanned Aircraft System MQ-9 Predator B Fact Sheet*.

220. Blasco, X., et al., *A New Graphical Visualization of< i> n</i>-Dimensional Pareto Front for Decision-making in Multiobjective Optimization.* Information Sciences, 2008. **178**(20): p. 3908-3924.

221. Minder, B. and T. Coleman (2012) *Unmanned Aerial Vehicles: Underutilized and Untapped*. Emergency Management.

222. Underwood, M. (2010) *US Air Force Drone Assisting with Haiti Relief*. Technorati.

223. Madrigal, A.C. (2011) *Inside the Drone Missions to Fukushima*. The Atlantic.

224. Howard, C. (2012) *Unmanned Aerial Vehicles Help Law-Enforcement Agencies Save Money, Catch Criminals*. Avionics Intelligence.

225. New York City Department of Planning. *2010 Primary Land Use: Each Borough's Lot Area by Land Use*. 2010 [cited 2010 May 10]; Available from: http://www.nyc.gov/html/dcp/pdf/landusefacts/landuse_tables.pdf.

226. Federal Aviation Administration, *Air Traffic Activity System*: Washington, D.C.

227. King, D.W., A. Bertapelle, and C. Moses, *UAV Failure Rate Criteria For Equivalent Level of Safety.* 2005.

228. Federal Aviation Administration, *Aeronautical Information Manual*. 2012, Washington, D.C.

229. Federal Aviation Administration, *Procedures for Handling Airspace Matters JO 7400.2J*. 2012: Washington, D.C.

230. Smethers, M. and F. Tomasello, *European Commission Unmanned Aircraft System (UAS) Panel Process Discussion Paper*. 2011, European Aviation Safety Agency.