Developing a Risk Assessment Tool for Unmanned Aircraft System Operations

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Abstract

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The development of a web-based risk assessment tool for unmanned aircraft system operations in the national airspace is presented. Threats to human safety from midair collisions and ground strikes are the focus of the risk model. The project's intent is to assist in determining applications that leverage the strengths of current unmanned aircraft technology while mitigating the weaknesses so as to meet or exceed the safety and economic viability of manned aircraft. The validity of the risk model is demonstrated by comparison to historical data when available. The intended use of the tool is discussed and risk assessments are presented for several example scenarios. Resources for gathering the required information are surveyed and material is developed to aid a general audience in performing a risk assessment.

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Chapter 1

INTRODUCTION

The past several decades have seen significant advances in unmanned aircraft system (UAS[1]) technology. In the last 10 years there has been a corresponding increase in the their use by militaries around the world. The adoption of UAS for non-military purposes, however, has been quite slow. This trend has been especially true in the U.S. where concerns over their safe integration into the national airspace system (NAS) have often stifled efforts to employ UAS for the purposes of private industry, academia, and domestic government applications. While the complete integration of UAS is still years away, there are currently many practical uses for unmanned aircraft whose associated risk is equal to or better than that of manned aircraft. Reliable and realistic methods of evaluating risk must be developed in order to allow further development and use of UAS while ensuring public safety. This thesis documents the development and web-based implementation of a tool for assessing the risk of potential UAS operations. The University of Washington Autonomous Flight Systems Laboratory (AFSL) intends the product to be a useful tool for determining UAS applications that are viable from the related perspectives of risk and economics.

1.1 Current UAS Policy

Without a thorough understanding of the risks involved, regulations on the flight of UAS in US airspace have thus far been highly prohibitive. Policy was set forth in a September, 2005 Federal Aviation Administration (FAA) memorandum [28], clarified in a 2006 notice [35], and replaced in March 2008 by the Interim Operational Approval Guidance [17]. Currently, the only avenue to receive approval of civil (i.e. commercial, academia) UAS operation is through a special experimental airworthiness certificate. The special certificate is subject to operational limitations (e.g. line of sight operation, daylight hours, etc.) and is only

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[1] UAS is also used throughout this thesis to abbreviate the plural, unmanned aircraft systems.

issued “for the purposes of research and development, crew training, or market survey.” The procedure and guidelines for issuing a special experimental certificate are detailed in [31].

A second avenue, a certificate of authorization (COA), was closed to civil applications in 2005 by [28] but is still used for public (i.e. government/military) requests after the vehicle has been deemed airworthy by the FAA or DoD. A category that a minority of UAS may fall under is model aircraft (strictly non-business related), the use of which is dictated by [36]. Other documents of interests include NATO’s UAV Systems Airworthiness Requirements [6] and the European Aviation Safety Agency’s (EASA) statement on Airworthiness Certification of Unmanned Aircraft Systems [4].

UAS policy is currently being reviewed to develop a long-term approach to a fluid integration of UAS into the NAS. Several components of the NextGen Air Transportation System (ATS) should help facilitate this process in the coming years [7]. NextGen refers to the next generation of the NAS being incrementally implemented over the course of several years, with current mid-term goals set through 2018. Two key NextGen technologies that have the greatest potential to impact UAS integration are Automatic Dependent Surveillance-Broadcast (ADS-B) and 4D Trajectory Based Operations (TBO) [19, 8]. The FAA’s perspective on UAS has been supportive but cautious as indicated by the following excerpt from [28],

> *“The FAA supports UA flight activities that can demonstrate that the proposed operations can be conducted at an acceptable level of safety. AFS intends to approve COA applications... [if] a collision with another aircraft...is extremely improbable....[and] injury to persons or property along the flight path is extremely improbable. Acceptable system safety studies must include a hazard analysis, risk assessment, and other appropriate documentation that support the ‘extremely improbable’ determination.”*

1.2 Motivation

There are a number of obstacles to the full integration of UAS into the NAS. The most pressing technological challenges are "sense and avoid" (SAA) capability and command and control (C2) link liabilities [8]. Sense and avoid refers to the capability of an autonomous vehicle to detect objects, both stationary and mobile, that do not broadcast their position, which are in the vehicle's path (or otherwise on a collision course) and, if necessary, alter the vehicle's course to avoid a collision. Since the pilot of a UAS is not able to provide the "see and avoid" ability of an onboard pilot, the development of reliable SAA technology will be essential for UAS to gain full airspace access. Significant work has been done both in R&D of SAA technologies and in establishing qualifications for an acceptable SAA system [5].

Although most UA[2] will have low-level autonomy, a reliable communication link between the UA and the pilot is necessary for high-level control (navigation, tasking, air traffic control, etc.). In addition to improving the C2 link reliability, protocols must be developed to ensure safe and predictable behavior in the case of a lost-link. There is also much work to be done on the policy front. Guidelines are needed on airworthiness, crew training, operational protocols and how UAS will fit into the current and NextGen airspace structures.

Thoroughly addressing all of these issues, so that UAS may be routinely and safely incorporated throughout the NAS, will take years. In the mean time, standards and tools need to be developed that will, "enable the widest range of activity that can be safely conducted within the shortest rulemaking timeframe" (ASTM F38 Committee). Until new technologies are developed and a new system is in place, UAS operation approvals will continue to require mission specific risk assessments.

The purpose of the risk assessment tool presented in this thesis is two-fold. First, it seeks to provide UAS operators and airspace regulators with a simplified and trustworthy method of evaluating the safety of proposed UAS operations. Tools are needed that provide UAS operators with "documentation that support the 'extremely improbable' determination,"

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[2] UA is used to refer only to the aircraft, whereas UAS refers to the whole system inclusive of all ground-based equipment and any communication links.

since it is an essential part of the current approval process. By developing a tool to assess the risk of particular UAS operations, we hope to make the process of obtaining approval more efficient and more manageable.

The second objective is that the results of risk assessments performed using this tool would supply useful information to the aerospace community as future standards and guidelines are being developed. Successful regulation will prohibit unsafe operations while clearing the way for operations that do not pose a threat to public safety. Tools such as this web-based risk assessment will help determine what type of operations pose significant risk and which do not so that the policies being developed can reflect the risk associated with various UAS applications in order to maintain a high level of safety.

1.3 UAS Risk Assessment

It should be noted that no quantitative, and very little qualitative, meaning has been given to phrases commonly used by the FAA such as “acceptable level of safety”, “equivalent level of safety” and “extremely improbable.” What metric would be used for a quantitative safety standard is not even currently clear. Thus, any effort to provide UAS risk assessment tools is handicapped by the lack of clarity on what type of result is expected by the FAA.

Risk assessments for UAS operations have the same goal (public safety) as risk assessments for manned aircraft but must take into account the unique flexibility afforded by unmanned aircraft. The risk associated with operating aircraft may be divided between three primary groups: the crew and passengers aboard the primary aircraft, the crew and passengers of other nearby aircraft (termed transient aircraft in this thesis), and people and property on the ground. When considering the safety of manned aircraft, as long as the first group is always safe, the other two will follow. Manned aircraft must be extremely reliable because any crash or collision is a threat to the people onboard. The area in which the aircraft is operating does not affect the need for reliability [26].

When the crew and passengers are removed from the aircraft, the traditional approach of focusing on the safety of the people onboard the primary aircraft no longer applies. The risk of UAS operations depends not only on the reliability of the aircraft but also on the characteristics of the operating area (air traffic, pedestrians, buildings, etc.). Therefore, the regulations and policies developed for UAS must take both aspects into account if they are to protect the public without unnecessarily inhibiting the development and integration of UAS technologies. For example, policy that allows a 99% reliable UAS to operate over a densely populated area but prohibits a 95% reliable UAS from operating over a remote, unpopulated area would be inadequate. A successful policy must reflect the fact that the true risk is a product of both the aircraft and the operation for which it is used.

The model here will break the risk of UAS operations into three categories: transient aircraft collisions, pedestrian strikes and inhabited building strikes. Collisions within a fleet of UA operating in the same airspace will also be calculated as they could contribute to pedestrian and building strikes. The risk assessment tool will be available in a downloadable form (Excel spreadsheet) and a more fully-featured web-based implementation. In the absence of established UAS safety standards, the risk assessment results in this project will use the expected number of fatalities per flight hour as the primary safety metric. In an attempt to give this expectation a more tangible interpretation, an associated insurance risk will also be calculated. Other expectations such as the number of midair collisions and building strikes will also be given.

A similar risk-based approach to analyzing the safety of UAS operations was taken by researchers at North Carolina State University in the development of the System Level Airworthiness Tool (SLAT) [13]. The author also chose to focus on the expected number of fatalities per flight hour as the primary safety metric. The actual risk assessment examines the UAS in more detail at the system level in order to define a more complete approach to certification.

For the website to be an effective tool, it must be easy for users to properly perform a risk assessment. A user's guide has been developed to step users through the process of filling out a risk assessment. Each piece of information requested is clearly explained in the guide to avoid any ambiguity. Once the needed information is clearly explained, the more significant task is directing users where to find that information. Links are provided to the best available resources for each set of information required. When appropriate, the links are accompanied by an explanation of the conceptual goal of the information so that users will understand how to use the information they find to get the needed data. The guide is included as Appendix A.

Chapter 2

RISK ASSESSMENT FRAMEWORK

This project must be placed into the context of the larger framework of UAS risk analyses as a variety of approaches could be taken. In this chapter we aim to give a big picture view of risk analysis and how it could be implemented depending on the particular application and the goals of the risk assessment. What aspects of UAS risk are addressed by this model and how the model might be adapted for other purposes will then be articulated.

2.1 Risk Assessment Goals

The formulation of risk assessment criteria is different depending on the end goal of the assessment. The information required and the underlying assumptions depend on the purpose of the model. The tool developed by the AFSL is designed to estimate the risk to human life, which means other forms of risk are necessarily neglected. For applications in the NAS, human safety may be the first and most important goal, but it is not the only factor to consider. From an economic perspective, significant costs can be incurred when no harm is done to humans.

Property damage represents an economic risk that is closely correlated to human safety but is not included in the current model. This cost is a relatively easy addition to the risk model since the same incidents that can cause fatalities (e.g. building and vehicle strikes) will also be the main cause of property damage. The environmental impact of UA crashes must also be considered before beginning an operation. Even in cases when no people or property are in danger, a cost is associated with environmental damage and cleanup. Including this cost into a risk assessment will require a study of past aircraft crashes to determine how the damage and cleanup cost should be calculated and how it can be estimated for UA crashes.

In most cases, the largest economic risk to UAS operators other than human safety is not damage caused *by* the aircraft but the damage done *to* the aircraft. The aircraft themselves, not including the related operating systems, cost on the order of tens of thousands (\$35,000 for an RQ-11 Raven) to tens of millions (\$11,000,000 for an MQ-9 Reaper and \$35,000,000 for an RQ-4 Global Hawk). While an operation which saw Global Hawks crashing weekly in a desert may be viable by human safety standards, it clearly would not be viable by business standards. An assessment that aims to predict the overall *economic* risk must make these costs a key part of the risk model.

These costs were not included in the study here because estimating comprehensive financial risks is outside the scope of this project. Furthermore, incorporating such costs might obfuscate the human safety aspect, which is the main focus of the project. The dollar amounts attached to the human safety risks are not primarily intended to predict the actual cost to insure against human injury (although they may prove useful for this purpose as well) so much as they are intended to be a more tangible representation of the safety risk. The dollar amounts associated with these other risks, such as property damage and aircraft replacement, would be predictions of actual costs rather than representing a more fundamental danger (i.e. human safety). For this reason, the best way to include such costs is in a parallel result or a completely separate calculation rather than combining them into a single figure with the human safety result.

2.2 Causal Factors

There are numerous ways in which a UAS may fail, and many incidents are the result of multiple factors. In order to improve the reliability of UAS, understanding these specific factors is important so that they may be individually addressed. The causes may be grouped into several categories such as operator error, improper maintenance, loss of communication, equipment failure, weather, etc. Differentiating between types of failures will allow operators and regulators to understand how failure rates might be lowered over time. As a system matures, some causes of failure are largely mitigated (e.g. equipment failure), while other causes tend to persist (e.g. weather). The Air Force Class A Aerospace Mishap records, maintained by the Judge Advocate General's office, are a useful resource for tracking the distribution of mishap causes over time for a particular aircraft system [3]. The Air Force Safety Center offers less detailed mishap data for a number of aircraft, which is useful for finding overall failure rates over time [1].

The Air Force Research Laboratory used these resources in a recent study of Predator mishaps. The study revealed that the first several years of operation were dominated by equipment failures, many of which have been addressed. The system then moved into what the author identifies as a second era dominated by various human factors [21]. Once these causes were better understood, the training for new and current operators was refocused to address the human factors identified as common root causes. Since these changes were implemented, the Predator's Class A mishap rate (per flight hour) has steadily decreased with the greatest improvement being seen in the area of human factors [33]. This study demonstrates how understanding the causal factors of UAS failures can lead to significant improvements in system reliability, which affects both safety and operational costs.

The distribution of mishaps between causal factors is not considered by the risk model developed in this research because it has little effect on the human safety of the current aircraft system. A 'bottom-line' figure for crashes due to all types of failure (including human factors) was deemed sufficient for the purposes of this risk assessment. Those groups wanting to form a risk trajectory to determine when a system will reach a certain level of safety would want to examine the distribution more closely. Understanding the sources of system failures will allow UAS developers and operators to know where critical improvements must be made for a particular platform in order to achieve safety standards. The system level approach taken in [13] may be of interest for such purposes. An additional reason individual causes of failure were not considered in the risk assessment is to maintain the model's simplicity and ease of use. Every platform will have unique modes of failure and the classification of these failures varies between operators. Accommodating such a high degree of variance would add considerable complexity to the model with little gained in the way of utility.

One possible exception to this grouping is failure from loss of communication with the UA (lost-link). Link vulnerability is a major issue when considering the reliability of UAS and one that the FAA has singled out (along with sense and avoid) to be addressed before integration into the NAS moves forward. Since lost-link is expected with all UAS, many developers are implementing predetermined lost-link procedures that help to mitigate the danger of communication losses. Singling out this particular failure is worthwhile in cases where incident frequency is easily tracked by the operator. The effect of lost-link procedure reliability on safety risks could then be evaluated. This addition to the current risk model will be considered as a possible future improvement.

2.3 Flight Phase

A further distinction is sometimes made between mishaps based on the phase of flight in which they occur. A typical operation is broken down into taxi, takeoff, climb, enroute, descent, and landing (some operations combine climb with takeoff and descent with landing). Particular activities within the enroute phase, such as loiter, target tracking and target attack may also be specified in cases where they increase the likelihood of a mishap. Studies such as [21] indicate that while the majority of mishaps do occur enroute, a disproportionate number (relative to flight time) occur in other phases. The landing phase, in particular, tends to have a much higher mishap rate relative to the time spent in each phase.

The model considered here does not distinguish between mishaps in different phases of flight, which makes the implicit assumption that the failure rate being used excludes mishaps during particular flight phases that do not fit the general population profile (e.g. isolated airfields, restricted areas). For the purposes of public safety, neglecting the phases of flight that do not have a realistic possibility encountering humans or other aircraft is justifiable.

The taxi, takeoff and landing phases often take place through predefined paths over airports or airfields that are free of homes and pedestrians. If a particular UAS is prone to crash during takeoff, for example, the operator may choose to always perform takeoff in a restricted area free of pedestrians and populated buildings. This would mitigate the safety risks of mishaps during takeoff, meaning they should not be included in the overall failure rate since the area in which takeoff occurs does not fit the population profile of the general operating area.

Bird strikes, on the other hand, are a far greater risk during taxi, takeoff and landing, with 80% occurring below 1,000ft AGL and 96% occurring below 5,000ft AGL [34]. A risk assessment focusing on the total economic risk would need to consider mishaps during all phases of flight. While crashing UA on the runway is not a threat to public safety, doing so will result in expensive repairs and aircraft downtime. The failure rate for each phase would need to be specified individually since mishaps during different phases of flight will tend toward different causes and are likely to result in different costs. The repair/replacement costs are expected to be higher for enroute failures (which will likely destroy the UA) while takeoff and landing incidents often only require repair. The lack of pedestrians and populated buildings beneath takeoff and landing paths results in much less risk of causing a fatality or property damage during these flight phases.

2.4 Intended Use

Several additional qualifications should be noted on the intended use of the risk model developed in this thesis. Although the author aimed to retain a good deal of flexibility, the model was created with certain types of operations in mind. This choice was necessary because the risk profile differs so widely between an operation over a densely populated urban area and an operation over a sparsely populated wilderness area. Any risk model must be a simplification of a very complex problem. In the language of control theory, making this simplified model is something like linearizing highly nonlinear dynamics about some operating point. The "operating point" chosen for this calculation to most accurately model are operations over areas of relatively sparse population and air traffic. The assumptions made in the formulation do not hold as well for cases of high air traffic and population densities. The conservative nature of the model's assumptions causes the projected risk to increase at a rate faster than reasonably expected. See the discussion of the model's validity in Section 3.4.

Applications which the risk model is well suited to support are tasks such as geographic surveys, border patrol, disaster assessment, search and rescue, etc. The model was intentionally designed with this type of operation in mind. The reason being that these operations are the most economically viable for civil and public use. Aside from the large budgets available to militaries, they can justify the use of a UAS in situations where a manned aircraft might be less expensive because doing so often removes a human from harm's way. In domestic applications, where the danger of being shot down is not a real concern, UAS are only likely to find a niche in areas where they can provide an economic advantage. As

McGeer points out in [26], manned aircraft are actually quite affordable for most domestic applications, which means expensive and less reliable unmanned aircraft are not likely to unseat them anytime soon. Although the vision is not as exciting as futuristic depictions of robotic aircraft zooming over a metropolis, the majority of near-term uses for UAS will likely be in remote areas of low population often performing mundane tasks.

The risk calculation is more flexible when it comes to other aspects of the operation. It can handle a variety of operations, such as those which require a UA to loiter over a small area or fly a long distance route or a team of UA that patrol a large region. The risk assessment can include multiple operating areas, and each operating area can use multiple transient aircraft models to represent the airspace. This feature allows the tool to accommodate a wide range of operation profiles. For example, the operating area for a long distance flight would simply be a reasonably wide flight path (1-10km for most UAS). If the UA passes through areas of highly disparate population or air traffic densities, a series of ‘operating areas’ would be used to represent each significantly different area overflown (although if they are properly averaged, a single operating area would give the same result). Some applications may require a little creativity to fit the risk model. Oceanic operations, for instance, could model boats as buildings since they are essentially the same from the perspective of a risk assessment. The built-in air traffic resource has less flexibility, which is discussed in Subsection 4.2.3.

Chapter 3

RISK MODEL

3.1 Midair Collisions

The midair collision calculations used here are based on theory originally developed to predict the collision frequency of gas molecules as presented in [29]. This theory was similarly applied to air traffic in [9], [27] and [25]. The collision frequency between a single UA and transient air traffic is a product of the transient aircraft density, the combined frontal areas and the velocity of both the UA and the transient aircraft.

We define ρ_o and ρ_{ua} to be the density of transient aircraft and UA (respectively) per km^2, ϕ_o and ϕ_{ua} to be the frontal area in km^2 of the transient aircraft and the UA, V_o and V_{ua} as the velocity[1] in km/hr of the transient aircraft and the UA, ϵ_o and ϵ_{ua} as the collision avoidance (from 0 to 1) of the transient aircraft and the UAS.

To average the risk of a midair collision over all orientations, the frontal areas of the UA and the transient aircraft are recast as circles of radii $R_{ua} = \sqrt{\phi_{ua}/\pi}$ (km) and $R_o = \sqrt{\phi_o/\pi}$ (km). A collision will occur if the centers of the aircraft are within a distance $R_{ua} + R_o$. The UA then sweeps an effective collision area of

$$\begin{aligned} \phi_{col} &= \pi(R_{ua} + R_o)^2 \text{ (km}^2) && (3.1) \\ &= \pi(\phi_{ua}/\pi + \phi_o/\pi + 2\sqrt{\phi_{ua}\phi_o/\pi^2}) && (3.2) \\ &= \phi_{ua} + \phi_o + 2\sqrt{\phi_{ua}\phi_o}. && (3.3) \end{aligned}$$

To calculate the effective collision area between two identical UA within a fleet, we substitute ϕ_{ua} for ϕ_o to get

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[1] Although knots is the standard unit of speed in aeronautics, km/hr is used in developing the risk model for the sake of simplicity and consistency with other units. The website allows the user to select their units and then converts it to SI units for computation.

$$\phi_{col} = \phi_{ua} + \phi_{ua} + 2\sqrt{\phi_{ua}^2} = 4\phi_{ua} \text{ (km}^2\text{)}. \tag{3.4}$$

The effective volume swept by the UA per unit time is just the product of the collision area and the UA velocity. The expected number of collisions (without *any* collision avoidance measures) per unit time is then the number of transient aircraft (or other UAs) expected to be in the swept volume. At any instant, the effective collision volume is simply the space occupied by the UA. The expected number of transient aircraft also in that volume, assuming the transient aircraft are stationary, depends only on the air traffic density (aircraft per volume). The expected number of midair collisions with transient aircraft per UA flight hour would then be given by

$$F_{transient} = \rho_o \phi_{col} V_{ua}. \tag{3.5}$$

To correct for the fact that the transient aircraft are not stationary, but in fact are moving at a velocity V_o, V_{ua} is replaced by an average relative speed of

$$V_{rel} = \sqrt{V_{ua}^2 + V_o^2} \text{ (km/hr)}. \tag{3.6}$$

For collisions within a fleet of UA, this velocity is simply $V_{rel} = \sqrt{2}V_{ua}$. Notice that in typical cases where V_{ua} is much smaller than V_o, V_{rel} can be replaced by V_o without significant impact on the outcome. For typical cases in which $V_{ua} \leq \frac{1}{2}V_o$, the result would be changed by a factor of 1.1 or less. In the unusual case where the UA were traveling as fast as the transient aircraft, the result would be off by only a factor of $\sqrt{2}$.

To make the calculation more accurate in a wide range of operations, collision avoidance capabilities must be incorporated. Any UAS that are allowed to fly in non-restricted airspace will likely be required to be equipped with a transponder (such as the Microair T2000UAV-L) making them visible to air traffic control (ATC) and Traffic Collision Avoidance System (TCAS) equipped aircraft. Having a transponder will greatly reduce the risk of midair collisions between UA and TCAS equipped aircraft. In addition to a transponder (which broadcasts its own location but does not “see” nearby aircraft itself), UAS will eventually incorporate active SAA systems. These systems will enable the UAS to actively avoid collisions with transient aircraft and other UA whether or not they are cooperative.

Collision avoidance gained from the airspace structure or procedural separation will have to be incorporated into the UA collision avoidance and transient aircraft collision avoidance terms. The basic collision model assumes all aircraft fly randomly within the specified volume with no structural or procedural separation. Section 3.4 gives the effective collision avoidance of general aviation air traffic in today's NAS.

The expected number of midair collisions per flight hour is now given by

$$F_{transient} = \rho_o \phi_{col} V_{rel} (1 - \epsilon_{ua/o})(1 - \epsilon_o). \tag{3.7}$$

The expected number of collisions within the fleet per flight hour is given by

$$F_{fleet} = 2\rho_{ua} \phi_{ua} \sqrt{2} V_{ua} (1 - \epsilon_{ua/ua}), \tag{3.8}$$

where a distinction is made between the ability of the UAS to avoid collisions with other aircraft in the fleet ($\epsilon_{ua/ua}$) and with general air traffic ($\epsilon_{ua/o}$). This distinction is necessary because most UAS do not have effective SAA in general, but they do typically have methods of avoiding in-fleet collisions since the location and velocity of each UA is known by a centralized controller (or by each UA in some cases).

An extra precaution needs to be taken when computing the in-fleet collisions for a group of UA (or any aircraft). The above equation accurately describes the risk for a single aircraft within the group. If the calculation is applied to every aircraft in a group the result will be double the true expectation because every collision is double-counted, once for each aircraft involved. Thus, a factor of $\frac{1}{2}$ must be included when applying the estimate to group of UA.

3.2 Ground Collisions

The ground collision calculations (pedestrians and buildings) are a hybrid of the equations developed in [27], [25] and [32] to best represent general UAS operations. The risk to people and buildings from crashes due to system failures (i.e. not from midair collisions) is found by assuming the UA glides to the ground at maximum L/D (worst-case scenario). The risk to people on the ground from midair collisions assumes the UA will approach the surface in free fall. Thus the expected number of building and pedestrian strikes are composed of two calculations that take each case (glide and free fall) into account.

Since UAS tend to have high mishap rates during takeoff and landing, the failure rate used will only represent mid-flight failures if takeoff and landing are performed in a restricted area free of pedestrians. This distinction is made in order to avoid overestimating the risk. If takeoff and landing do not take place in a restricted area, then these mishaps should be included in the failure rate.

The expected number of pedestrian strikes per UA flight hour is given by

$$F_{ped} = \lambda \sigma_p A_{L_{Hp}} + F_{midair} \sigma_p A_{L_{Vp}}. \tag{3.9}$$

The expected number of building strikes per UA flight hour is given by

$$F_{bldg} = \lambda \sigma_b A_{L_{Hb}} + F_{midair} \sigma_b A_{L_{Vb}}, \tag{3.10}$$

where

$$\begin{aligned}
F_{midair} &= F_{transient} + F_{fleet} \text{ (collisions)} \\
A_{L_{Hp}} &= (w_{ua} + 2R_p)(L_{ua} + \frac{H_p}{\tan\gamma}) \text{ (km}^2\text{)} \\
A_{L_{Vp}} &= \pi(\frac{w_{ua}}{2} + R_p)^2 \text{ (km}^2\text{)} \\
A_{L_{Hb}} &= (w_{ua} + w_b)(L_{ua} + \frac{H_b}{\tan\gamma}) \text{ (km}^2\text{)} \\
A_{L_{Vb}} &= \pi(\frac{w_{ua}}{2} + \frac{w_b}{2})^2 \text{ (km}^2\text{)}
\end{aligned}$$

where λ is the UAS midair failure rate per flight hour (from all sources), σ_b and σ_p are the building and pedestrian densities (respectively) per km^2, F_{midair} is the midair collision rate per flight hour, A_{L_H} and A_{L_V} are the lethal areas in km^2 for aircraft gliding horizontally and falling vertically, A_b is the average building size in km^2, w_b is the average building width in km (defined as $w_b = \sqrt{A_B}$), H_b is the average building height in km, R_p is the radius of a person (defined as 2.5E-4km or 0.25m), H_p is the height of a person (defined as 1.75E-3km or 1.75m), γ is the UA glide angle without power, w_{ua} is the UA wingspan in km, and L_{ua} is the UA length in km.

3.3 Fatalities & Insurance

A successful risk assessment must communicate the results in a way that provides the user with a tangible sense for the risk involved. The most *important* result is the number of fatalities expected. Unfortunately, hearing a number like 2.3E-7 fatalities per flight hour will not mean much to most users. Is that good? Is that bad? Though doing so may sound insensitive, a simple way to make this number more tangible is to look at the cost to insure the operation. An amount of liability coverage is chosen per fatality, which results in a cost to insure the operation per flight hour. Many other factors could be considered in the liability coverage such as property damage, damage to transient aircraft, damage to the UA themselves, etc. However, the fatality liability will be the dominate cost and also the best indicator of the most important risks involved.

The expected number of fatalities[2] per flight hour is given by

$$F_{fat} = F_{transient} P_o + F_{ped} D_{ped} + F_{bldg} D_{bldg}. \tag{3.11}$$

The cost to insure the operations per flight hour is given by

$$C = F_{fat} I_{fat}, \tag{3.12}$$

where P_o is the average number of passengers on a transient aircraft, D_{ped} is the fatality rate for a pedestrian strike, D_{bldg} is the fatality rate for a building strike, and I_{fat} is the insurance liability per fatality.

3.4 Model Validation

To show that the midair collision model presented in Section 3.1 is a reliable method of estimation, results predicted by the model will be compared with historical data. Random collision theory was first shown to be a valid model for estimating aircraft collisions for VFR (visual flight rules) traffic in [9], which aimed to measure the degree to which human efforts at collision avoidance were effective. A slightly modified version of the original results, based

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[2] Assuming that striking an aircraft causes the death of all passengers.

on data from 1969-1978, is reproduced in Table 3.1. The same analysis is then performed on the most recent data available for general aviation (which generally operates under VFR).

Table 3.2 shows the number of midair collisions and the total hours flown by general aviation aircraft for each year from 1995 to 2005 [2]. To find the average air traffic density, we make the simplifying assumption that the total general aviation flight hours are spread evenly over 16 hours each day throughout the year (spreading them over a 24 hour period would underestimate the risk). The number of midair collisions predicted by random collision theory, assuming no collision avoidance, is then found for each year and compared to the historical results.

The effective avoidance from human efforts compared to the prediction can then be backed out from $F_{hist} = F_{pred}(1 - \epsilon_{ind})^2$ where ϵ_{ind} represents the effective avoidance for *each* general aviation aircraft. This division assumes that the net effect of collision avoidance can be attributed equally to each aircraft. For example, if all general aviation aircraft can avoid a collision 90% of the time ($\epsilon_{net} = 0.9$), then a collision between two general aviation aircraft should be avoided $90\% + 90\% \times 10\% = 99\%$ of the time ($\epsilon_{net} = \epsilon_{ind} + \epsilon_{ind} \times [1 - \epsilon_{ind}]$). Conversely, if we know collisions between two aircraft are avoided with effectives ϵ_{net}, then to determine the avoidance of each aircraft we must find an ϵ_{ind} between 0 and 1 which solves the quadratic equation $\epsilon_{ind}^2 - 2\epsilon_{ind} + \epsilon_{net} = 0$.

The second column, *Actual Collisions*, gives the number of general aviation midair collisions that occurred in the given year. The fifth column, *Predicted Collisions*, gives the number of general aviation midair collisions predicted by the model with no collision avoidance. The sixth and seventh columns, ϵ_{ind} and ϵ_{net}, then give the effective collision avoidance demonstrated by the historical data (*Actual Collisions*) compared to the model's prediction. The collision avoidance figures are a measure of how much better (fewer collisions, positive ϵ) or worse (more collisions, negative ϵ) the historical results are than what was predicted by the model. In other words, the effective avoidance is the value that makes the model's prediction match the historical data exactly.

The predicted collisions were obtained by assuming a generalized model for all general aviation aircraft. The majority of general aviation is comprised of small single-engine piston aircraft but the category also includes turboprops, jets, rotorcraft, gliders and others [2].

Year	**Actual Collisions**	**Flight Hours**	**Avg Traffic**	**Predicted Collisions**	ϵ_{ind}	ϵ_{net}
1969	23	25351000	2893.9	24.8	0.04	0.07
1970	32	26030000	2971.5	26.1	-0.11	-0.22
1971	27	25512000	2912.3	25.1	-0.04	-0.08
1972	24	26974000	3079.2	28.1	0.08	0.14
1973	24	29974000	3421.7	34.6	0.17	0.31
1974	32	31413000	3586.0	38.1	0.08	0.16
1975	28	32024000	3655.7	39.5	0.16	0.29
1976	30	33922000	3872.4	44.4	0.18	0.32
1977	34	35792000	4085.8	49.4	0.17	0.31
1978	33	36600000	4178.1	51.7	0.20	0.36
Avg	**28.7**	**30359200**	**3465.7**	**35.5**	**0.10**	**0.19**

Table 3.1: Midair collision data for general aviation in U.S. airspace from 1969-1978 [9].

A frontal area of 25m^2, an average speed of 190kts and a service ceiling of 5km were used with the entire U.S. as the operating area (9.83 million km^2). The model's size, speed and ceiling are a little higher than the average single-engine piston aircraft to account for the larger multi-engine, turboprop and jet aircraft included in the category. A slightly different representative aircraft was used by Anno in [9] to produce the data of Table 3.1, although both are appropriate to their era. Slightly different methods of computing the collision cross section and relative velocity were also used.

With no collision avoidance assumed ($\epsilon_{net} = 0$), the model's predictions are conservative but on the right order of magnitude. We find that within general aviation, avoidance through airspace structure, regulations and the pilot's ability to see and avoid, the actual number of collisions are reduced by 59% ($\epsilon_{net} = .59$). The $\epsilon_{ind} = .36$ indicates that on average, a single aircraft/pilot can be attributed with 36% effective collision avoidance. This effective avoidance is an improvement over the avoidance for general aviation from 1969-1978 which

Year	**Actual Collisions**	**Flight Hours**	**Avg Traffic**	**Predicted Collisions**	ϵ_{ind}	ϵ_{net}
1995	29	24000000	4109.6	49.7	0.24	0.42
1996	35	24900000	4263.7	53.5	0.19	0.35
1997	28	25500000	4366.4	56.1	0.29	0.50
1998	27	25500000	4366.4	56.1	0.31	0.52
1999	31	29700000	5085.6	76.1	0.36	0.59
2000	25	29100000	4982.9	73.0	0.41	0.66
2001	12	25400000	4349.3	55.6	0.54	0.78
2002	10	25500000	4366.4	56.1	0.58	0.82
2003	20	25900000	4434.9	57.8	0.41	0.65
2004	22	24800000	4246.6	53.0	0.36	0.59
2005	20	23100000	3955.5	46.0	0.34	0.57
Avg	**23.5**	**25763636**	**4411.6**	**57.2**	**0.36**	**0.59**

Table 3.2: Midair collision data for general aviation in U.S. airspace from 1995-2005 [2].

averaged an $\epsilon_{net} = 0.19$.

The fact that midair collisions did in fact occur (just 30 years ago) at a rate very close to that predicted by random collision theory demonstrates the applicability of the theory. Although the current data shows some improvement over that of the 1970s, random collision theory still provides an order-of-magnitude approximation. When information about the aircraft's collision avoidance (established experimentally) can be incorporated, the prediction will become more accurate. For example, in Table 3.3 the model is used to predict collisions for general aviation from 1995-2005 with an assumed avoidance of 50% (the true value was shown to be 59%). The average prediction error is reduced by 78%, from 33.7 to 7.5. The third column of Table 3.3 gives the predicted number of midair collisions with an assumed collision avoidance of $\epsilon_{net} = .50$. The fourth column, *Error*, lists the error of that prediction compared to historical results, while the last column, *Original Error*, lists the error of the prediction from Table 3.2 where no avoidance is assumed.

Year	**Actual Collisions**	**Prediction with Avoidance**	**Absolute Error**	**Original Error**
1995	29	24.8	4.2	20.7
1996	35	26.7	8.3	18.5
1997	28	28.0	0.0	28.1
1998	27	28.0	1.0	29.1
1999	31	38.0	7.0	45.1
2000	25	36.5	11.5	48.0
2001	12	27.8	15.8	43.6
2002	10	28.0	18.0	46.1
2003	20	28.9	8.9	37.8
2004	22	26.5	4.5	31.0
2005	20	23.0	3.0	26.0
Avg	**23.5**	**28.6**	**7.5**	**33.7**

Table 3.3: Predicted midair collisions with collision avoidance (U.S general aviation from 1995-2005).

Midair collisions involving air carriers, which operate under instrument flight rules (IFR), are far less frequent and show human efforts to avoid midair collisions have been highly effective. For this reason, the midair collision model of Section 3.1 does not accurately approximate the collision rate for IFR traffic. Several reasons exist for the significant difference in how effective human efforts have been between the two categories. Virtually all air carriers ($\geq$ 10 seats) are required to be equipped with TCAS which uses transponder signals to notify the pilot of potential collisions or “intruder aircraft”. Additionally, air carriers spend the vast majority of their time in Class A airspace which requires the aircraft to be under ATC control and operating under IFR. Finally, most air carrier flights follow simple point-to-point flight paths at set altitudes. All of these characteristics are in contrast to general aviation flights which are not always equipped with transponders and typically operate in Class E airspace which does not require ATC communication or IFR. Not surprisingly, air carriers avoid midair collisions far better because far more technological and systematic collision avoidance is in place for air carrier operations.

General aviation provides a better baseline for comparison to *near-term* UAS operations than air carriers. Until the ADS-B equipped NextGen ATS is implemented and much more effective SAA technology has been developed, UAS are not likely to achieve anywhere near the avoidance capability of air carriers. UAS are also likely to have variable flight paths that may wander and change altitudes depending on the application, much more similar to general aviation than air carriers. More importantly, the niche operations that UAS are likely to fill can accept less reliable avoidance and still present risk-levels equivalent to or less than the risk-levels of current manned aircraft operations. Air carrier-like avoidance is not necessary for all applications in order to protect human safety.

As discussed in Section 2.4, this collision model was selected primarily with applications in mind that avoid areas of high population and air traffic. Although nothing about the collision theory changes in areas of high air traffic, the estimation model includes some safe assumptions intended to give a conservative baseline. When applied to high risk areas, the conservative nature of the model simply stands out more. If the estimation were to be 50% high when the insurance risk per flight hour is on the order of $10, the difference is hardly noticed. The same 50% overshoot is noticed much more when the insurance risk is on the order of $1,000 or even $10,000. That is not to say a risk assessment for an urban operation is not meaningful. While the financial difference between $10,000 per flight hour and $15,000 per flight hour may not be insignificant, the model is only intended to give an order-of-magnitude approximation. For the purposes of a risk assessment, either value indicates that flying a UAS in that location is probably not a good idea when manned aircraft can be hired for far less cost.

3.4.1 Appropriate Avoidance

To best use the midair collision model, the task remains to determine appropriate collision avoidance levels, ϵ_{ind}, for UAS with current technology. Although good estimates should be used for factors such as frontal area and operating speed, extreme accuracy in these numbers will not meaningfully affect the estimate. Assigning significance to such small changes implies an accuracy beyond that inherent in the highly simplified model. The model's accuracy can be most significantly improved by incorporating a sound approximation of collision avoidance. The model provides a conservative starting point that will become more accurate as more information is gathered on the reliability of UAS collision avoidance.

Determining an appropriate value for ϵ_{ind} will be the responsibility of the individual using the risk assessment tool. Reasonable values will vary between UAS and should always be based on data gathered experimentally. The effectiveness of the avoidance for the same UAS may also vary between operations. For example, a UAS operating in Class A airspace is required to have a transponder and be under ATC control which means other aircraft will always know the relative location of the UAS, and avoidance should be highly effective. If the same transponder-equipped UAS were operating outside of Class A airspace, there is no guarantee the transient aircraft will be TCAS equipped, which means they may be blind to the UA and avoidance will be less effective. If an operation is shown to have low risk (and associated cost) with little avoidance capability, then highly effective (read expensive) collision avoidance is not actually needed for that application to maintain a high level of safety.

3.4.2 Bird Strike Comparison

While midair collisions between two aircraft are relatively rare, bird strikes take place on a daily basis. An average of nearly 20 bird strikes per day were reported between 2004 and 2008 [34]. These incidents provides a much larger historical sample for comparison to the midair collision model. With thorough information on bird traffic and when strikes occur (altitude, phase of flight, etc.), the midair collision model can be tailored to give the expected number of bird strikes. The results can serve to validate and further refine the collision model. Understanding how the midair collision model of Section 3.1 can be used to estimate bird strikes will be helpful in developing a complete economic risk model as discussed in Section 2.1. Allowing bird strikes to be considered separately from a general mishap rate will also improve the human safety risk model.

Information on wildlife strikes reported by the FAA and the Air Force can be used to determine how the scenario should be modeled. The information needed to apply the model includes the size and altitude range of the space being modeled, average bird size and speed, average aircraft size and speed, average bird air traffic (volumetric density), average aircraft traffic (volumetric density) and the collision avoidance of both birds and aircraft with respect to one another.

The area to be modeled is the entire U.S. airspace below some altitude. With 72% of bird strikes occurring at or below 500ft AGL and 92% occurring at or below 3,000ft AGL, the bird strike model should clearly focus on a low altitude range. One approach to determining the average traffic below some altitude is to use an API for monitoring air traffic such as FlightAware FlightXML. Another approach is to consider the number of daily takeoffs and landings and approximate how long the average aircraft takes to climb past the altitude range of interest. In this approach, general aviation aircraft that spend time below the set altitude outside of takeoff and landing must be given special consideration which may lead one back to an air traffic API.

For bird and aircraft size and speed, a single average model can be used, or several models representing broad classes (as in Sections 4.1 and 4.2.2). Although pilots are sometimes warned of larger bird flocks spotted on radar, in general they have very little ability to avoid a collision (as demonstrated by the bird strike frequency) so aircraft should be assigned a collision avoidance of 0. The bird's collision avoidance should also initially be assumed to be zero. While birds likely alter their course at times to avoid collisions, a conservative baseline will first be established without including any assumptions about the collision avoidance. If the model is able to give an order of magnitude approximation, the effective collision avoidance can then be backed out.

The missing element in this analysis has been reliable data on bird air traffic. A relationship has recently been established with the Bird/Wildlife Aircraft Strike Hazard (BASH) team at the Air Force Safety Center that may help in providing the needed information. The Air Force collected detailed data on bird populations in order to develop the Bird Avoidance Model (BAM), which is currently used in the Avian Hazard Advisory System

(AHAS). The initial data was collected on the populations of 60 key bird species and used to compute the average bird mass in an area (ounces/km^2). Some consideration must be given to how population data can be used to produce a reliable estimation of bird air traffic. Information such as average bird mass and typical behavior (with regard to time in the air) should allow a reasonable conversion to be made. Further discussion with the BASH team on this issue should prove beneficial by gaining from their experience with the subject.

Chapter 4

IMPLEMENTATION

Once the mathematical model was developed for estimating risk, it had to be implemented in such a way that a non-technical person can easily use the model to get an accurate estimate. The estimate that the tool outputs will only be as good as the data used in the model. This chapter describes how the model was implemented to be a user-friendly web-based tool. Comments are also made on how the user should determine some of the less obvious pieces of information. A more thorough set of instructions on using the risk assessment tool may be found in the user's guide in Appendix A.

4.1 UAS Model

All UAS participating in an operation must be represented by a single UAS model in the current calculation. The user can either input the UA specifications manually or select one of three predefined models shown in Table 4.1. The small, medium and large UA models are based loosely on the Insitu ScanEagle, General Atomics MQ-1 Predator and Northrop Grumman RQ-4 Global Hawk respectively. The intention is not for the models to represent these actual UAS, but rather to give the user an idea of the size of UA each category represents. The frontal area, mean speed, wingspan, length and glide angle will be automatically populated if one of these models is chosen. The only parameters of the UAS model left for the user to provide are the collision avoidance and the failure rate (defined below). The number of UA, group flight hours and operating altitude range will all be specified for each operating area to provide greater flexibility in the model.

Two significant parameters that deserve a word of explanation are the failure rate and collision avoidance. The user is asked to group all causes of a loss of control into the failure rate. Whether the problem is a loss of power, avionics error, or a loss of communication, any event other than a midair collision causing the pilot to lose control of the UA is considered

UAS Model	**Frontal Area**	**Mean Speed**	**Wingspan**	**Length**	**Glide Angle**
Small	0.4m^2	54kts	3m	1.5m	3.2°
Medium	10m^2	81kts	15m	8m	2.3°
Large	25m^2	324kts	35m	15m	1.9°

Table 4.1: Predefined UAS models.

part of the failure rate. The collision avoidance term, ϵ_{ind}, is a catch-all term since a variety of approaches to avoidance are being developed and tested for UAS. Regardless of the method, the bottom line is what percentage of the time the UAS can avoid an otherwise imminent collision. In general, this collision avoidance is for non-cooperative aircraft that are not broadcasting their position or velocity information. If the operator has good reason to believe the UAS will know the position and velocity of transient aircraft, then the collision avoidance term may take this fact into consideration. As mentioned in Section 3.4, distinguishing between the net avoidance of two aircraft and the individual avoidance of the UAS is an important detail.

4.2 Operating Area

In order to make the website flexible enough to suit a wide variety of UAS applications, multiple operating areas may be included in a single risk assessment. The results are presented for each area individually and for all areas collectively. This feature can be used when separate teams of UAS are being used in multiple areas simultaneously or when a single team of UA will operate in an area diverse enough that capturing the population profile in a single model is difficult (for more on the use of multiple operating areas see Section A.2). The operating area can be divided into two components, the surface model and the airspace model.

4.2.1 Surface Model

The first component of the operating area is the surface model. The size of the operating area may be specified by the user directly or determined using the interactive map feature described in Subsection 4.2.3. For each operating area, the user is asked to provide the structure density and average size and height, as well as the (unsheltered) pedestrian density. The *Resources* page and user's guide suggest a number of websites (e.g. the U.S. Census Bureau) and other resources (e.g. Google Earth) to help determine this information.

The most subjective aspects of the surface model are the fatality rates for pedestrian and building strikes. The fatality rates indicate the likelihood that a strike will result in a fatality. The fatality rates will vary greatly between UA and, in the case of building strikes, between operating areas. Both are impacted by characteristics of the UA such as weight, speed and size. Additionally, some UAS are designed intentionally to be frangible; basically, to break on impact in order to minimize the risk to people and property. For building strikes, the user also needs some idea of how densely the buildings are populated and how they would be effected by a strike (how sturdy are they). Considering all of these factors, the user needs to supply the expected number of fatalities that would result from a building strike.

4.2.2 Airspace Model

The second component of the operating area is the airspace model, which is the most complicated part of the calculation. The basic approach is to use representative aircraft for the traffic through the operating area. A transient aircraft model includes the number of aircraft per unit area (within the operating altitude range), the frontal area, mean speed, passenger load and collision avoidance. The user must determine the collision avoidance of the transient aircraft because it will vary depending on how the UAS is equipped. A simplified model of US airspace based on three representative categories of aircraft (commercial jet, regional jet, general aviation) will be available, primarily as a point of reference since most UAS will be operated in areas of reduced air traffic. The three models were selected to represent an average aircraft in the category. Users can model an operating area by modifying the generic airspace model or by specifying their own transient aircraft models with respective densities. The risk from each representative transient aircraft is then calculated as well as the risk of an in-fleet collision between two UA.

Aircraft Model	**Frontal Area**	**Mean Speed**	**Passenger Load**
General Aviation	22m^2	173kts	3
Regional Jet	80m^2	432kts	45
Commercial Jet	175m^2	437kts	135

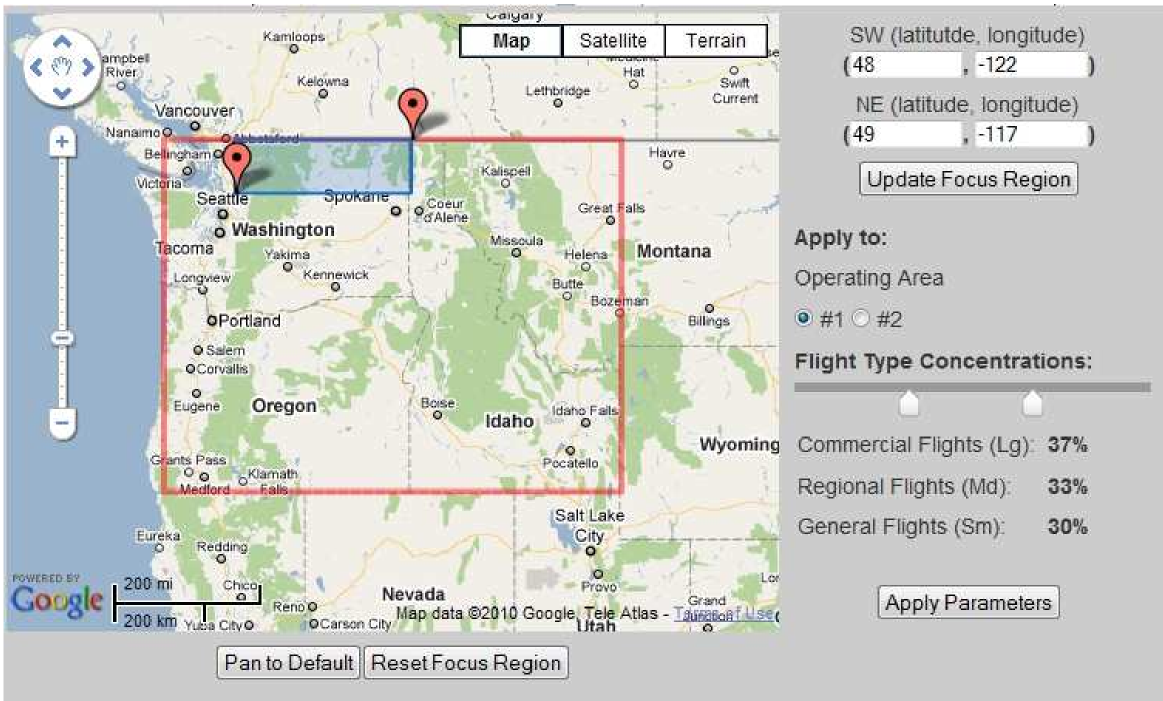
Table 4.2: Predefined transient aircraft models.

4.2.3 Automated Air Traffic Data

An interactive tool has been developed that determines the air traffic from historical data for a specific operating area and altitude range specified by the user. The data were collected using the FlightAware FlightXML API. The user sets the operating area by selecting the region on an interactive map or by specifying the latitude and longitude of two corners. The size of the operating area and the average density of air traffic for the set altitude range is then calculated from an air traffic database. In this study we consider the Northwest US and Georgia as two representative regions. This capability can be extended to the rest of the NAS at additional cost. Figure 4.1 shows the user interface for the automated air traffic tool. The Matlab code that calculates the air traffic for a selected region is included as Appendix B. The code includes some portions that have been commented out as the corresponding features have not yet been implemented.

4.2.4 Air Traffic Mapping

As an additional tool for analyzing the air traffic of a region, ways of mapping the traffic density were also explored. Mapping has not been incorporated into the web-based tool but could be a useful resource to users trying to avoid high-risk airspace or could be used as part of a risk-based path planning algorithm. Providing users with a visualization of where the greatest danger of midair collision is will allow them to adjust the operating area accordingly. Example maps of the Northwest U.S. air traffic density are shown in Figures 4.2, 4.3 and 4.4. The code used to sort the air traffic and produce these maps is included as Appendix C.



SW (latitutde, longitude)
(48, -122)
NE (latitude, longitude)
(49, -117)

Apply to:
Operating Area
● #1 ○ #2

Flight Type Concentrations:

Commercial Flights (Lg):	**37%**
Regional Flights (Md):	**33%**
General Flights (Sm):	**30%**

Figure 4.1: Automated air traffic tool.

4.2.5 Validity of Historical Data

An important question is how well the historical data predicts future air traffic. Would basing the prediction on scheduled air traffic instead of past data be more accurate? Using flight schedules to forecast air traffic through a specific region turns out to be very complicated and does not yield a reliable prediction. Although some flights are scheduled far in advance, many others are not, and flight schedules are frequently changed or delayed for a variety of reasons. While flight routes (jet routes and victor airways) between most airports are predetermined, there is no guarantee an aircraft will actually use one of these routes. Even if a specific route were followed, the same route can be flown at multiple flight levels. This scenario is for Class A airspace under ATC control, the most predictable of all public airspace. Class E airspace, where most general aviation flights take place, is even more difficult to predict.

For most uses of the risk assessment tool, flight history is the simplest and most accurate

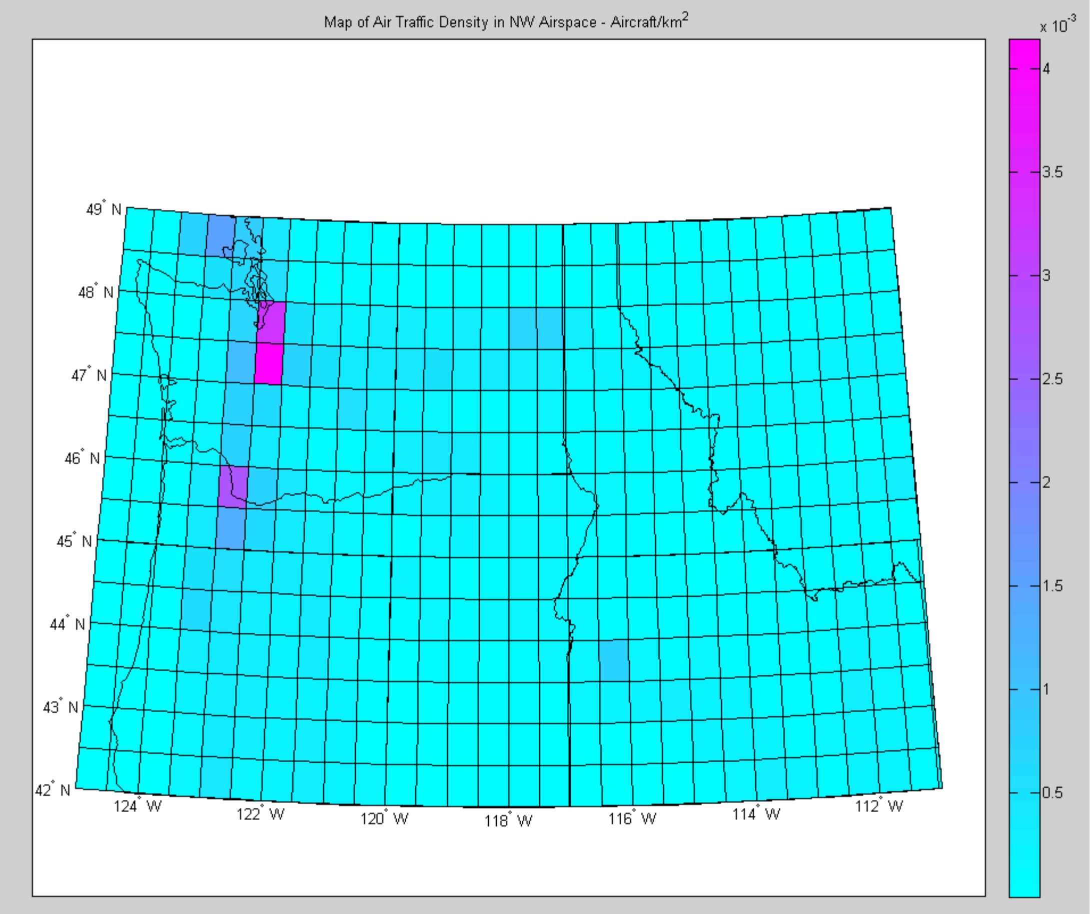


Figure 4.2: Grid of Northwest U.S. air traffic density.

way to estimate future air traffic. Once a large enough database of past air traffic is compiled, a reliable figure for the average traffic though any 3D region can be found quickly. To test the concept, a small database was gathered for the airspace over the Northwest United States. Over a ten day period, a snapshot of the traffic was taken every hour which recorded the time-stamped latitude, longitude and altitude of every aircraft. This database allows the air traffic data to be organized however is needed for a particular application.

Several factors must be considered to ensure the historical data are used appropriately for a prediction. The three most important variables are time of day, weekday or weekend and time of year. Air traffic varies greatly over the course of a day, so a UAS that operates

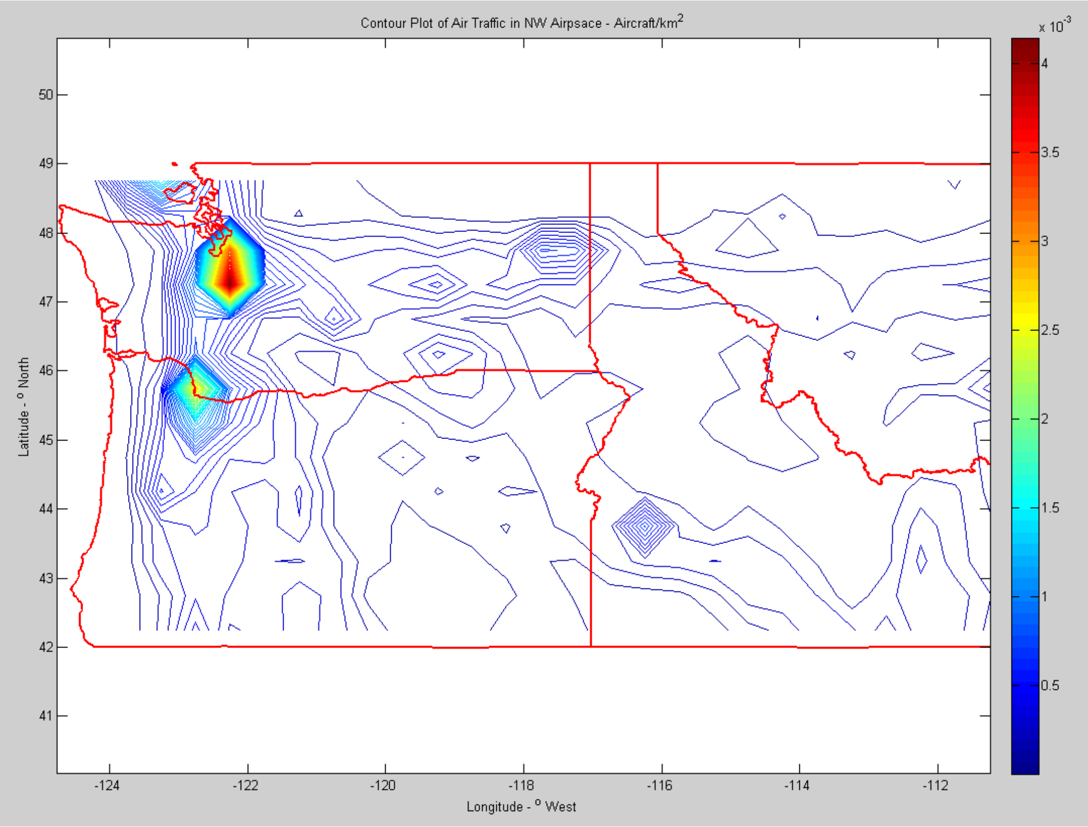


Figure 4.3: Contour plot of Northwest U.S. air traffic density.

around the clock will have a lower average risk (per flight hour) than one that operates during daylight only. Over the course of a week the number of commercial flights is relatively stable but general aviation flights increase significantly on weekends. Aside from spikes for holiday travel, some seasonal variation takes place in air traffic, especially for general aviation. All of these variables should be considered so that the data being used for the prediction is a good representation of the actual operation. The current database is too small to meaningfully incorporate any of these adjustments, but they can easily be included in the estimation routine if a larger database is established. With a large enough database, one can limit the data being used for the prediction to days and times that are similar to the planned operation time.

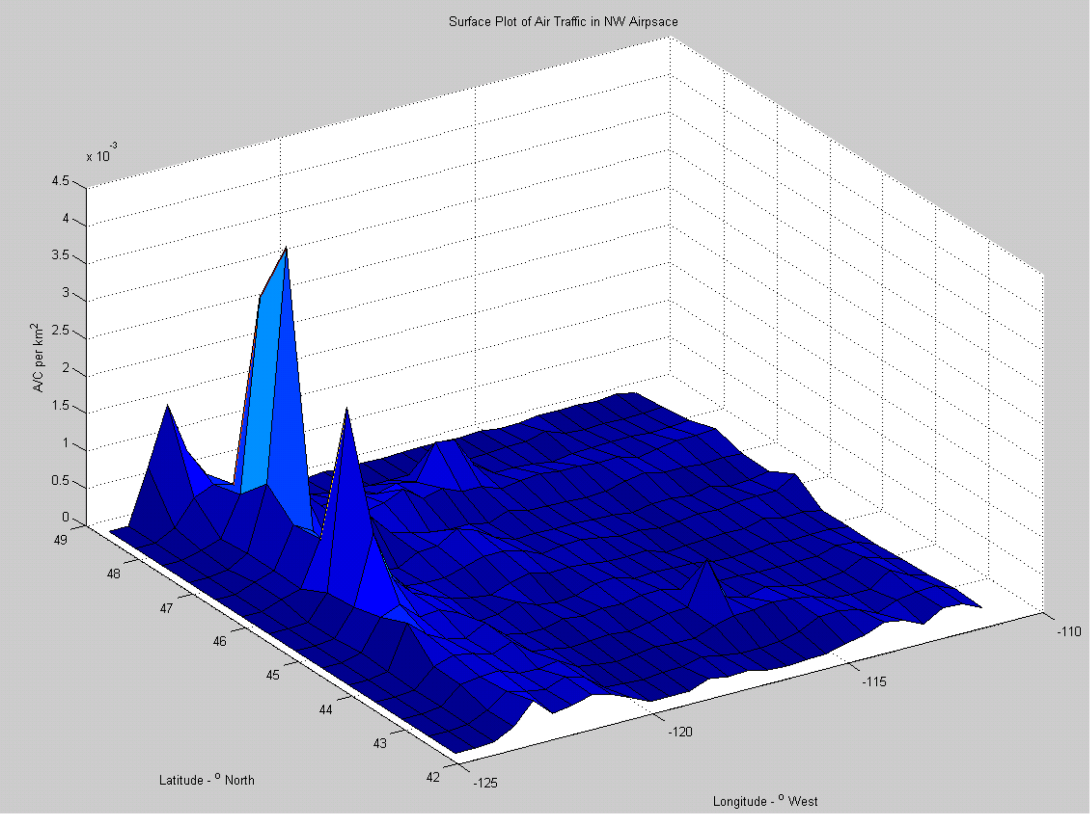


Figure 4.4: Surface plot of Northwest U.S. air traffic density.

4.3 Website Features

Several other features of the web-based implementation are worth briefly noting. In order to use the web-based risk assessment tool, a user may create an account or login as a guest. Creating an account allows the user to save calculations for future use or modification. Minimal information is requested during account setup so that the AFSL can know what groups are using the risk assessment tool and so that the user's privacy is respected. In order to support the model developed for the risk assessment and to promote a risk based approach to UAS regulation and operation, the site also contains a *References* section which directs users to a number of relevant resources.

Chapter 5

SAMPLE RESULTS

This chapter presents sample calculations for three scenarios. The first two scenarios are operations which fit the intended use of this tool and the third is an operation which does not.

5.1 Scenario 1: Border Patrol

In recent years a number of technologies have been adapted by the United States Customs and Border Protection (CBP) Agency to help protect and monitor U.S. coastlines and borders, including UAS as one of the key technologies to augment the agencies' border patrol capabilities. Several General Atomics MQ-9 Reapers, for instance, are being operated over the Arizona-Mexico border to spot smugglers and people entering the country illegally [16]. According to recent reports, the government is planning to expand the use of UAS to other border regions as well,

> *"Customs and Border Protection has said it intends to increase unmanned aircraft systems across the country this year, and it expects a complete network of the unmanned planes all along the border by 2015.*
>
> *Officials boasted about the Predators' effectiveness in a fact sheet published in February 2009. They reported that Predator B planes have flown more than 1,500 hours and contributed to the seizure of more than 15,000 pounds of marijuana and the apprehension of more than 4,000 undocumented people."* [18]

This scenario will serve as our first sample case.

5.1.1 UAS Properties

The wingspan, length and operating speed of the MQ-9 Reaper are readily available as 20m, 11m and 162kts [10]. By referencing pictures and diagrams of the Reaper, see Figure 5.1, we can estimate the frontal area with the landing gear up. We start by drawing a triangle encompassing the propeller and tail assembly. The width across the top of the triangle is 6.8m and the height from top to bottom of the tail is 3m, giving an area of $\approx 10\text{m}^2$. The wings will be approximated as two rectangles 0.5m high and 8.5m wide (20m wingspan minus ∼3m overlapped by the tail section). The total frontal area is then approximately 18.5m^2. The frontal area approximation is depicted in Figure 5.2.

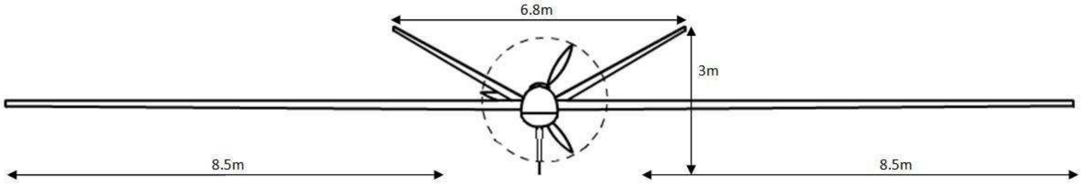


Figure 5.1: MQ-9 Reaper Frontal Area Dimensions.

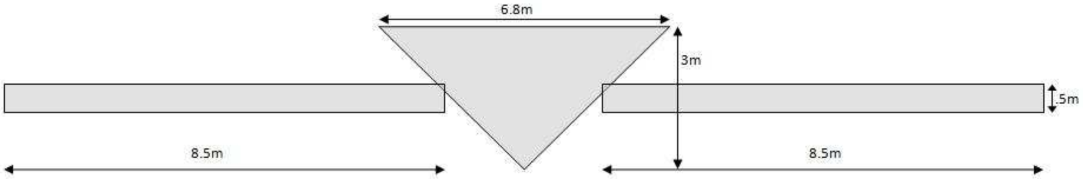
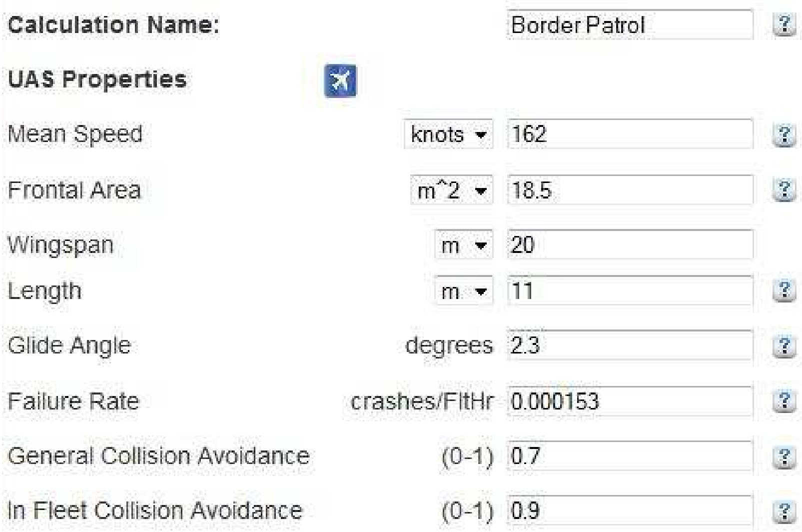


Figure 5.2: MQ-9 Reaper Frontal Area Approximation.

The lift to drag ratio is not published, but this information would certainly be available to a group operating the Reaper. We can safely approximate the lift to drag ratio at about 25:1 which yields a glide angle of $\tan^{-1}(1/25) = 2.3°$. Based on the Reaper's flight history, it has an established Class A mishap ($1M+ damage or fatality) rate of 15.3 per 100,000 flight hours (1.53E-4 crashes/flt hr) [14]. The UAS control center is certain to know the location of all Reapers in the air, and every Reaper is operated by its own pilot, so in-fleet collision avoidance should be very reliable. To allow for the possibility of a communication loss, an in-fleet collision avoidance of 90% will be used.

Reapers are equipped with Mode C transponders, which will aid other aircraft in avoiding collisions with the Reaper, but this fact does not mean that the Reaper will be able to sense other aircraft. The UAS pilots can monitor air traffic using ground-based radar, but since UAS are not designed to perform aggressive maneuvers and occasionally suffer communication losses, we will assign the UAS a collision avoidance of only 0.7 (70% effective). This figure is an estimate for the purposes of this example. In a real risk assessment, the operator must determine the collision avoidance term based on experimental or historical data. All of the UAS properties needed for the risk assessment have now been accounted for (see Figure 5.3).



Calculation Name:		Border Patrol
UAS Properties		
Mean Speed	knots	162
Frontal Area	m^2	18.5
Wingspan	m	20
Length	m	11
Glide Angle	degrees	2.3
Failure Rate	crashes/FltHr	0.000153
General Collision Avoidance	(0-1)	0.7
In Fleet Collision Avoidance	(0-1)	0.9

Figure 5.3: UAS properties in web-based risk calculator.

5.1.2 Operating Area

The CBP operates four MQ-9 Reapers along the 600km Arizona-Mexico border. We will assume they patrol the territory within 20km of the border (distance between the border and the UAS base in Sierra Vista) which gives a 12,000km^2 operating area. A typical operating altitude for the Reaper during this type of observation is 5.5-7.5km (FL180-FL246). The Reaper can operate at much higher altitudes, but we are only interested in the range being used for this particular operation. Since details on the CBP's use of the Reapers are not published, we will consider the case where three of the four Reapers are in the air at any given time around the clock. Over the course of one year, this schedule results in 26,280 flight hours.

To determine the population density, we will use the data available from the U.S. Census Bureau, refined by the information we can gather from Google Maps satellite images. Looking at the 5-digit zip-code population data for the area along the border will give us a baseline population density. The population and home densities for the zip codes along the border are shown in Table 5.1. The average population density is 4.6 people/km^2 and the average housing unit density is 1.9 homes/km^2. If the zip codes for the three biggest cities on the border (Douglas/Agua Prieta, Nogales & Yuma/San Luis) are excluded we lose only 7% of the land area while avoiding 48% of the population. This assumption leaves a population density of 2.6 people/km^2 and 1.4 homes/km^2.

Assuming the Reapers do not operate over the three aforementioned cities (other than takeoff and landing near Nogales) is justifiable because they focus on illegal border crossings in more remote stretches, away from checkpoints and land-based law enforcement. Focusing the operation in these more remote areas minimizes the risk to the public and allows the UAS to complement the CBP at their weakest points. The home density can be used for the overall building density if we assume everyone in the population is either an exposed pedestrian or in their home at any given time. Considering most people spend the majority of their time indoors (school, work, home), we will take 10% of the population (0.26 people/km^2) to be exposed pedestrians and the remaining 90% to be indoors. The average housing unit then has 1.7 people inside at any given time.

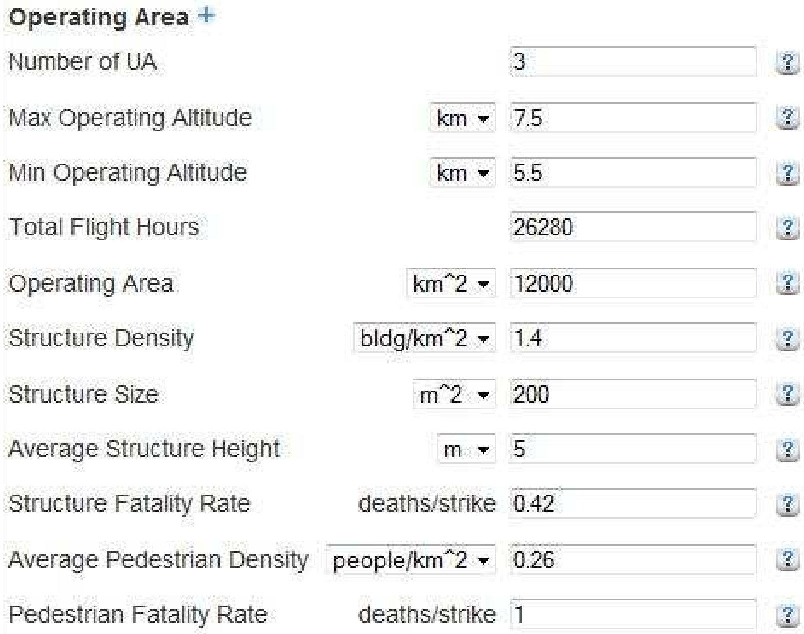
Since the Reaper is a heavy, sturdy aircraft that moves at high speeds, the pedestrian strike fatality rate will be taken as 1 (i.e. 100%). The building structure offers some protection to people indoors, but the size/weight/speed combination of the Reaper still poses a threat. Since all buildings are being modeled as homes we will estimate that a strike will result in the death of 25% of the people inside which gives a fatality rate of 0.42 deaths/strike. The average home can be taken as having a 200m^2 footprint and being 5m high. All of the operating area parameters have now been determined (see Figure 5.4).

Zip Code	**Area (km^2)**	**People/km^2**	**Population**	**Homes/km^2**	**Homes**
85608	1275.2	0.1	98	0.0	49
85607	947.9	22.3	21117	7.4	6990
85603	703.0	12.2	8577	6.3	4424
85615	590.6	11.1	6544	4.7	2805
85624	972.6	1.4	1314	0.8	789
85621	629.8	36.3	22881	11.5	7246
85634	7477.9	0.8	6063	0.3	2021
85633	870.7	0.2	134	0.1	67
85321	6133.8	0.8	4973	0.5	3079
85365	6737.8	5.4	36161	3.1	20812
85350	270.8	53.7	14556	12.5	3378
Totals	**26610**	**4.6**	**122420**	**1.9**	**51660**

Table 5.1: Population Data for Arizona Zip Codes on the Border.

5.1.3 Transient Aircraft

To estimate the air traffic in the region, we will use Flight Explorer Personal Edition and consult regional aeronautical charts. The altitude range under consideration is in Class A airspace so any air traffic through the region will be equipped with a transponder and most should be visible to the Flight Explorer tracking system (though some military flights, for instance, may not show up). Monitoring the airspace over Southern Arizona reveals that very little air traffic exists near the border. Figure 5.5 shows typical traffic for Southern Arizona. Most of the air traffic that is present passes over Nogales or Yuma which have already been excluded from our operating area. Aeronautical charts of the region show



Operating Area +

Number of UA		3
Max Operating Altitude	km	7.5
Min Operating Altitude	km	5.5
Total Flight Hours		26280
Operating Area	km^2	12000
Structure Density	bldg/km^2	1.4
Structure Size	m^2	200
Average Structure Height	m	5
Structure Fatality Rate	deaths/strike	0.42
Average Pedestrian Density	people/km^2	0.26
Pedestrian Fatality Rate	deaths/strike	1

Figure 5.4: Operating area properties in web-based risk calculator.

the only jetway (high altitude airway) that crosses the Arizona border, J92, originates at Tucson International and passes over the border at Nogales, not in our operating space.

A large portion of the airspace is sectioned off as restricted or military operation areas (MOAs). This restriction certainly influences the meager air traffic at low altitudes but most restricted areas and MOAs do not extend above FL180 into Class A airspace so the lack of high altitude air traffic is mostly natural. Monitoring the air traffic for several hours a day over three days (a larger sampling would be needed for a ‘real’ risk assessment), only two aircraft briefly passed over the region of interest but were not in the altitude range of interest. Based on this sampling, we can conservatively estimate that the probability of an aircraft being in the region of interest is no more than 10% which gives an expected air traffic per area of $0.1/12,000 \approx 8 \times 10^{-6}$ aircraft/km^2.

Given the altitude range, the air traffic will be divided close to evenly between the commercial jet and regional jet classes. The risk calculator’s predefined models will be used for both classes. As discussed in Section 3.4, all air traffic in Class A airspace will be under

ATC control operating under IFR and equipped with effective collision avoidance systems and practices. A conservative collision avoidance of 0.95 (95% effective) will be assigned to each transient aircraft model. All of the transient aircraft parameters needed for the risk assessment are now accounted for (see Figure 5.6).

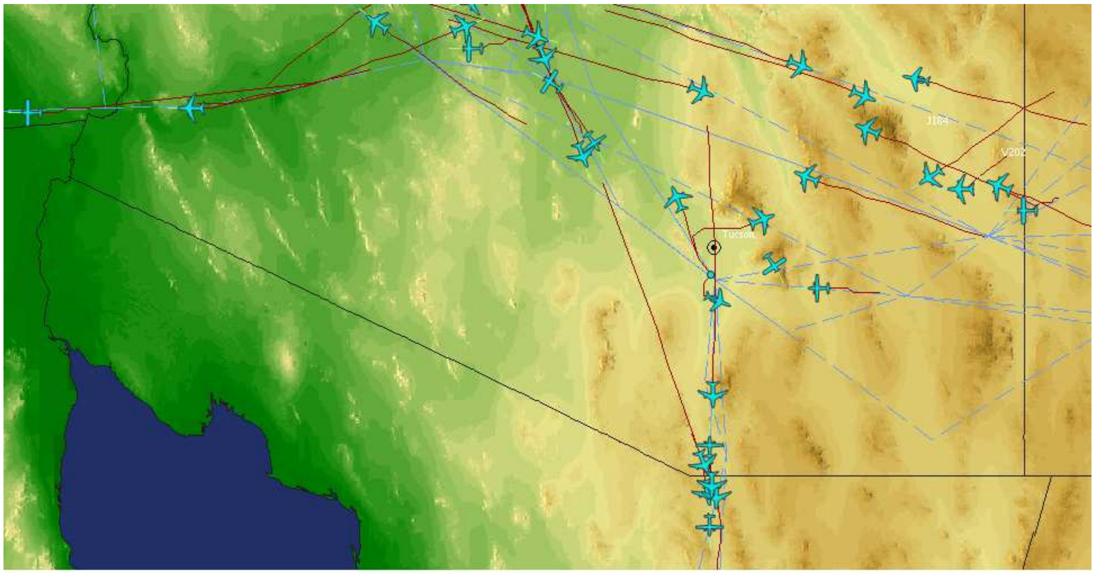


Figure 5.5: Airspace over Southern Arizona (from Flight Explorer PE).

5.1.4 Risk Assessment Results

Using these parameters, the risk calculator predicts 1×10^{-9} midair collisions per UA flight hour or one collision every 30,000 years of operation. The predicted pedestrian strike rate is 4×10^{-8} per UA flight hour or roughly one strike every 950 years. Building strikes are expected to happen at a rate of 1×10^{-6} per UA flight hour or one every 38 years. These events result in 6×10^{-7} fatalities per UA flight hour or one every 63 years of operation. If every fatality is covered by a $10 million insurance policy, the price to insure the operation is roughly $6 per UA flight hour, which gives an annual cost of about $156,000 for the team of Reapers. This cost is intended to be a more tangible expression of human safety risk rather than an estimation of what any actual insurance policy would cost.

Transient Aircraft 1

Density / Area	planes/km^2	4.167e-07
Mean Speed	knots	432
Frontal Area	m^2	80
Passenger Load		45
Collision Avoidance	(0-1)	0.95

Transient Aircraft 2

Density / Area	planes/km^2	4.167e-07
Mean Speed	knots	437
Frontal Area	m^2	175
Passenger Load		135
Collision Avoidance	(0-1)	0.95

Figure 5.6: Transient aircraft properties in web-based risk calculator.

These risk-associated costs are undoubtedly quite small compared to the overall costs of operation since the Reaper itself costs $10-20 million each (depending on what is included). The hourly insurance risk is in fact much less than the cost of paying a UAS pilot to operate the Reaper. This result does not mean that the operation is completely safe, but rather it indicates a, presumably, acceptable risk-level for this operation. Note that manned aircraft with the same reliability present far too much risk, regardless of where they are operated, since four major loss-of-control incidents are expected during the 26,280 hours of annual operation. However, as evidenced by the risk-assessment, the operation can accept such low reliability for UAS because of the area in which the operation is based. If a Reaper goes down over the specified region, it is very unlikely to strike a person or inhabited building. This result is exactly what happened when the CBP lost their first Reaper in 2006 [12].

5.2 *Scenario 2: Environmental Monitoring*

Environmental monitoring has been a popular non-military application for UAS in recent years. Unmanned aircraft have been used to monitor wildfires, assess damage from natural disasters, perform geomagnetic surveys, gather atmospheric data, and other environmental applications. As an example case, we will consider a team of ScanEagle UAS taking part in environmental monitoring over Northeast Washington. This risk assessment will be for wildfire detection, but the process is essentially the same for mapping, search and rescue or other low altitude operations.

5.2.1 UAS Properties

Since one the predefined UAS models available in the risk calculator represents aircraft of approximately the size of the ScanEagle, we can simply select the Small UA model and have most of the UAS properties automatically filled in. As an example, the frontal area estimation will still be demonstrated, even though the model's default value is used. The wingspan, length and fuselage diameter are available ([22], [30]) but not the propeller diameter or winglet height which must be approximated by the their size relative to known dimensions in pictures of the aircraft. Figure 5.7 shows how the frontal area may be approximated (the 0.3m diameter is for the propeller, which is larger than the 0.18m fuselage). The given dimensions yield an approximate area of 0.38m^2 which is quite close to the 0.4m^2 predefined frontal area for the Small UA model.

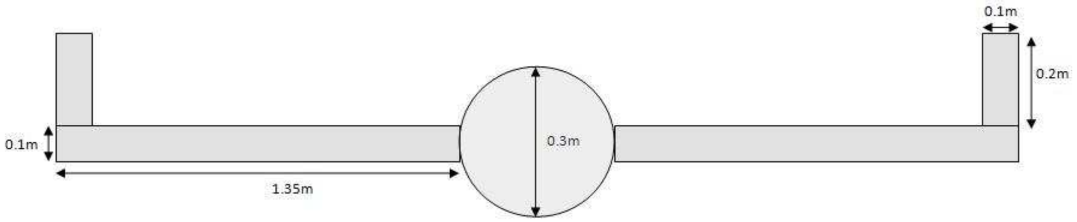
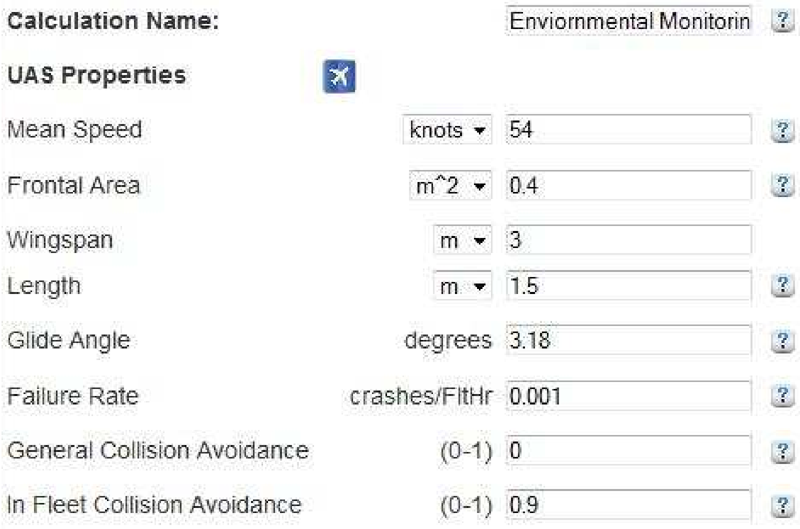


Figure 5.7: Frontal area approximation for ScanEagle.

A crash rate of 1 per 1,000 flight hours will be used for the calculation. Although the Navy does not officially track reliability data for the ScanEagle, loss rates have been reported between 1 in 214 flight hours and 1 in 500 flight hours [15]. These figures are overly pessimistic for a crash rate because they account for more than typical loss of control incidents such as damage from failed launches and recoveries or any other reason an aircraft may be deemed not airworthy.

Working under the assumption that the path planner, whether centralized or distributed, will have knowledge of every UA's location and velocity, an in-fleet collision avoidance of 0.9 will be used. We cannot be so optimistic about ScanEagle's collision avoidance with general air traffic since reliable SAA technology is still being developed. For this reason an effectiveness of 0 will be assumed for the UA's avoidance of general air traffic. However, since ScanEagles are now equipped with ultra-light custom designed Mode C transponders, most transient aircraft will be effective in avoiding the ScanEagles. This issue will be addressed in the transient aircraft properties.



Calculation Name:		Enviornmental Monitorin
UAS Properties		
Mean Speed	knots	54
Frontal Area	m^2	0.4
Wingspan	m	3
Length	m	1.5
Glide Angle	degrees	3.18
Failure Rate	crashes/FltHr	0.001
General Collision Avoidance	(0-1)	0
In Fleet Collision Avoidance	(0-1)	0.9

Figure 5.8: UAS properties in web-based risk calculator.

5.2.2 Operating Area

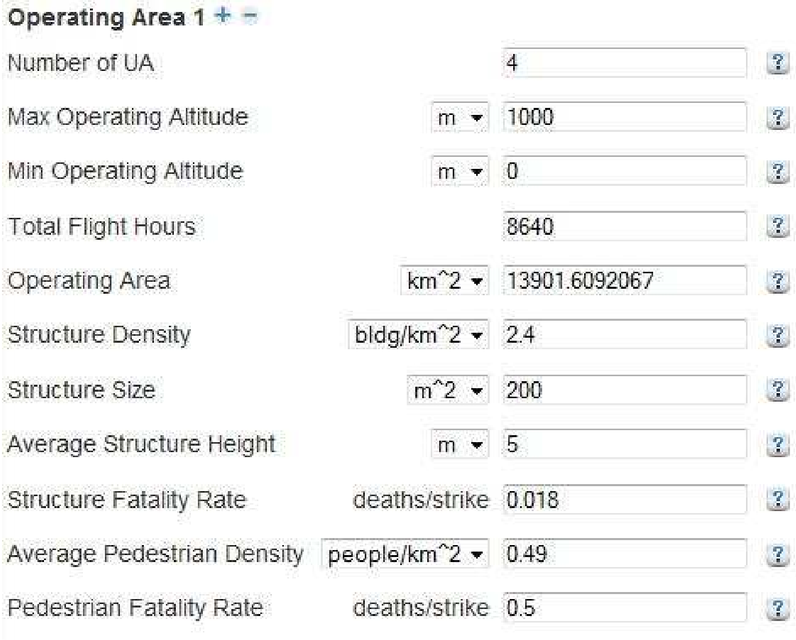
To demonstrate the website's ability to consider multiple operating areas for a risk assessment, we will consider two areas of wildfire concern in Eastern Washington. The first is the area around Colville National Forest with its north boundary at 49°N, south boundary at 48.1°N, east boundary at 117°W and west boundary at 118.9°W. The second region will be the southeast corner of the state with its north boundary at 47°N, south boundary at 46°N, east boundary at 117°W and west boundary at 119°W.

ScanEagles typically operate around 1500ft (457m) for imaging operations [20], so an altitude range of 0-1000m will be used. A generous range is chosen to include all aircraft posing a threat to the team of UA and to ensure the data returned by the automated air traffic tool is not artificially low or high. Although the ScanEagle can likely stay within several meters of a commanded altitude, looking only at air traffic in such a narrow range would not be an accurate representation. Since the automated air traffic data is based on "instantaneous" samples rather than full flight paths (which are not available), a narrow altitude range or too small of a geographic region essentially creates fickle results prone to exaggeration in either direction.

A team of four ScanEagles will be used in each of the operating areas over a sixth month period (the length of Washington's official wildfire season). Each UA will operate for 12 hours a day, seven days a week which gives a total of (4UA × 6months × 30days/month × 12hours/day) 8,640 flight hours in each operating area.

Data from the U.S. Census Bureau is used to determine the population densities by gathering the data from each zip code in the operating areas. For the Colville National Forest region, the average population density is 4.9 people/km^2, and the building density is 2.4 homes/km^2. For the Southeast Washington region, the average population density is 8.4 people/km^2, and the building density is 3.3 homes/km^2. The building densities only consider housing units, but this approximation will give an accurate model if the entire population is assigned to be an exposed pedestrian or in a housing unit. Estimating that the average person spends no more then 10% of their time outdoors, 10% of the population will be considered pedestrians, and the remaining 90% will be divided among the housing units (and accounted for in the fatalities/building-strike figure).

This estimation gives a pedestrian density of 0.49 per km^2 for the Colville region, and the average housing unit has 1.8 people inside. The pedestrian density for Southeast WA is 0.84 per km^2 with an average of 2.3 people in every building. The ScanEagle's relatively small size, light weight (around 40 lbs) and low operational speed must be taken into account when choosing the expected fatality rates. Here we will assume a pedestrian fatality rate of 50% (0.5 deaths/strike). Most homes would be effective in protecting the people inside from a ScanEagle size aircraft. Assuming the aircraft penetrates the building 10% of the time and in those cases causes the death of 10% of the people inside, the building-strike fatality rate is roughly 2×10^{-2} deaths/strike in both regions.



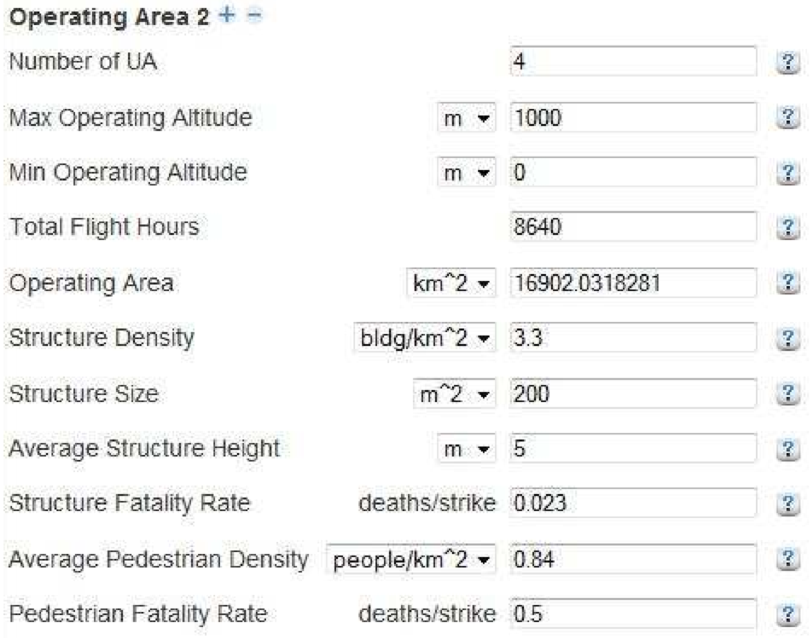
Operating Area 1

Number of UA		4
Max Operating Altitude	m	1000
Min Operating Altitude	m	0
Total Flight Hours		8640
Operating Area	km^2	13901.6092067
Structure Density	bldg/km^2	2.4
Structure Size	m^2	200
Average Structure Height	m	5
Structure Fatality Rate	deaths/strike	0.018
Average Pedestrian Density	people/km^2	0.49
Pedestrian Fatality Rate	deaths/strike	0.5

Figure 5.9: Colville operating area properties in web-based risk calculator.

5.2.3 Transient Aircraft

Since both operating areas are within the region where air traffic data is available, the automated map tool will be used. After opening the map interface with the Show Map



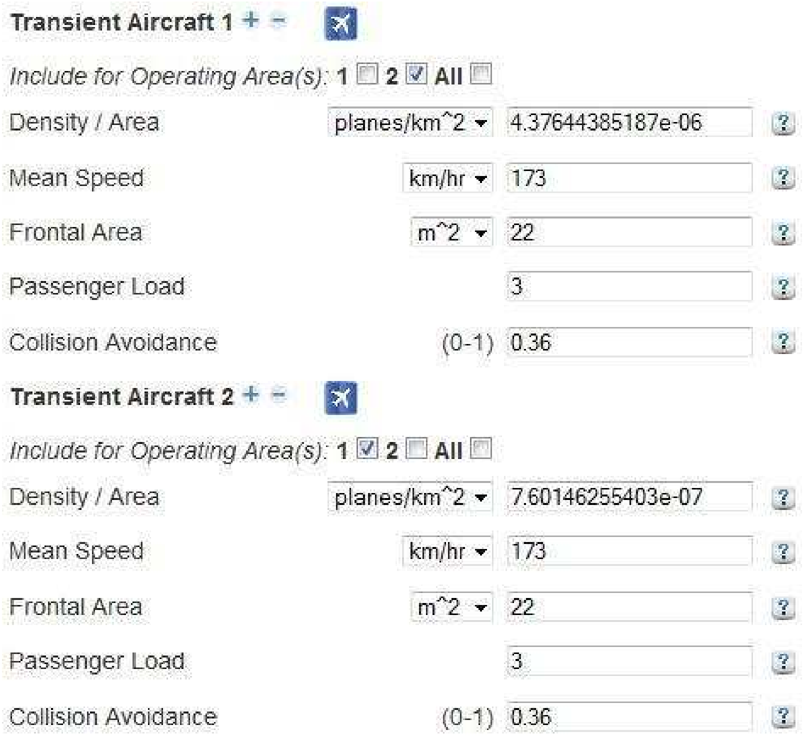
Operating Area 2

Number of UA		4
Max Operating Altitude	m	1000
Min Operating Altitude	m	0
Total Flight Hours		8640
Operating Area	km^2	16902.0318281
Structure Density	bldg/km^2	3.3
Structure Size	m^2	200
Average Structure Height	m	5
Structure Fatality Rate	deaths/strike	0.023
Average Pedestrian Density	people/km^2	0.84
Pedestrian Fatality Rate	deaths/strike	0.5

Figure 5.10: Southeast WA operating area properties in web-based risk calculator.

tab along the right hand side of the calculation page, we specify the latitude/longitude boundaries and select which operating area is being modeled. Since the ScanEagle's typical altitude range is so low for imaging operations, any transient aircraft in the operating space will be assumed to be under the general aviation category. Using the slider bar to set commercial and regional jet traffic to 0% will set the distribution to 100% general aviation.

Based on the historical data for the specified regions and altitude ranges, the automated air traffic tool gives an aircraft density of 8×10^{-7} aircraft/km^2 in the Colville region and 4×10^{-6} aircraft/km^2 in Southeast WA. The only remaining parameter to be filled is the transient aircraft collision avoidance. Since the ScanEagle is equipped with a Mode C transponder, general aviation's collision avoidance with the ScanEagle is expected to be on par with historical rates for the class as found in Section 3.4, which averaged 36% effectiveness.



Transient Aircraft 1

Include for Operating Area(s): **1** ☐ **2** ☑ **All** ☐

Density / Area planes/km^2 4.37644385187e-06

Mean Speed km/hr 173

Frontal Area m^2 22

Passenger Load 3

Collision Avoidance (0-1) 0.36

Transient Aircraft 2

Include for Operating Area(s): **1** ☑ **2** ☐ **All** ☐

Density / Area planes/km^2 7.60146255403e-07

Mean Speed km/hr 173

Frontal Area m^2 22

Passenger Load 3

Collision Avoidance (0-1) 0.36

Figure 5.11: Transient aircraft properties in web-based risk calculator.

5.2.4 Risk Assessment Results

Colville National Forest

For the Colville region (operating area 1), the predicted midair collision rate is 5×10^{-9} per UA flight hour or one collision every 25,000 wildfire seasons. Between midair collisions, building strikes and pedestrian strikes, the overall predicted fatality rate is 1×10^{-7} per UA flight hour or one every 1,200 wildfire seasons. If every fatality is covered by a $10 million insurance policy, the price to insure the operation is $1.10 per UA flight hour which gives an annual cost of $9,500 for the team of four ScanEagles.

Southeast WA

For the region in Southeast WA (operating area 2), the predicted midair collision rate is 3×10^{-8} per UA flight hour or one collision every 4,400 wildfire seasons. Between midair collisions, building strikes and pedestrian strikes the overall predicted fatality rate is 2×10^{-7} per UA flight hour or one every 400 wildfire seasons. If every fatality is covered by a \$10 million insurance policy, the price to insure the operation is \$2.47 per UA flight hour which gives an annual cost of \$21,000 for the team of four ScanEagles. Again, these costs are intended to be a more tangible expression of human safety risk rather than an estimation of what any actual insurance policy would cost.

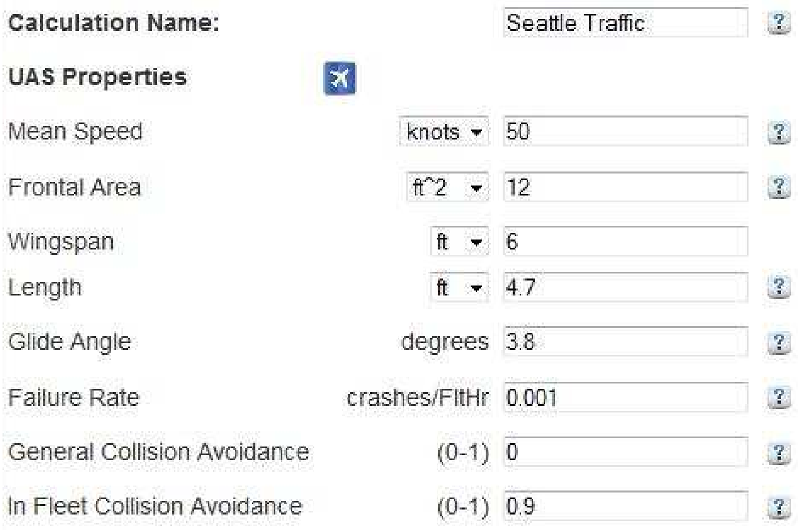
5.3 Scenario 3: Traffic Monitoring

The previous two examples represented the type of operations for which UAS are feasible near term solutions. The following example will demonstrate why many other suggested uses for UAS are expected to be less viable in the near term from the perspectives of safety and economics. While they may have technical merit and excellent potential benefits, risk assessments, such as the one presented here, reveal significant safety issues that will prevent regulatory approval and public acceptance. One such application is the use of UAS to monitor traffic in urban areas, which has been proposed by individuals in academia [11, 23] and explored by some governmental agencies [24]. This scenario will serve as a final sample case.

5.3.1 UAS Properties

Several case studies and trials have selected MLB's BAT 3 for traffic monitoring projects, so its specifications will be used here. The manufacturer lists the BAT 3's speed as 35-60kts, so an operational speed of 50kts will be assumed. The aircraft has a 6ft wingspan, 4.7ft length and 2ft height. Since no dimensioned drawings are available, the frontal area will be conservatively approximated as a 6ft×2ft rectangle giving an area of 12ft^2.

Data is not published on the BAT 3's glide angle or failure rate, although a group operating the aircraft would either have this information or determine it during testing. We will assume a lift to drag ratio of 15:1 which yields a glide angle of $\tan^{-1}(1/15) = 3.8°$. A failure rate of one mishap per 1,000 flight hours, representative of this class of UAS, will be assumed. The BAT 3 does not have collision avoidance ability with non-cooperative aircraft, aside from the pilot's ability to see and avoid using onboard cameras, so a general collision avoidance of 0 will be used. Knowing the position of other traffic monitoring UA should allow very effective in-fleet collision avoidance, so a value of 0.9 will be assumed.



Calculation Name:		Seattle Traffic
UAS Properties		
Mean Speed	knots	50
Frontal Area	ft^2	12
Wingspan	ft	6
Length	ft	4.7
Glide Angle	degrees	3.8
Failure Rate	crashes/FltHr	0.001
General Collision Avoidance	(0-1)	0
In Fleet Collision Avoidance	(0-1)	0.9

Figure 5.12: UAS properties in web-based risk calculator.

5.3.2 Operating Area

The Seattle area will be used as the operating area since it is within the region for which air traffic data has already been collected. As depicted in Figure 5.14, the area being considered will include several major suburbs of Seattle in order to encompass the primary highway system. The size of the operating area and the transient aircraft densities are automatically populated by the interactive map feature. A team of four UA will be operated in an altitude range of 500ft to 3000ft. If the four aircraft monitor traffic from 6:00am to 10:00am and from 3:00pm to 7:00pm every day, they are airborne 11,680 hours per year.

Population figures will be based on global data for the 981XX area codes. This region does not match up exactly with the area shown in Figure 5.14, but the data will provide a good approximation. According to the U.S. Census Bureau, the 981XX area codes average 2,767 people/mi^2 and 1,270 housing units/mi^2. As in the previous two examples, the simplest way to model the population is to assume everyone is either outside (pedestrian) or in a housing unit. Since the region being modeled is very urban, 15% of the population will be assumed to be outside (10% was used in other example calculations) which gives a pedestrian density of 415/mi^2.

Dividing the remaining population evenly between the housing units results in 1.9 people inside the average housing unit. An average structure size of 2,000ft^2 and 30ft high will be used. Given the small size and weight (25 lbs) of the BAT 3, only 10% of aircraft that strike a building will be assumed to penetrate the structure, resulting in the death of 10% of the people inside. This estimation gives an average of 2×10^{-2} fatalities per building strike. For pedestrians a fatality rate of 50% will be assumed given the characteristics of the UA.

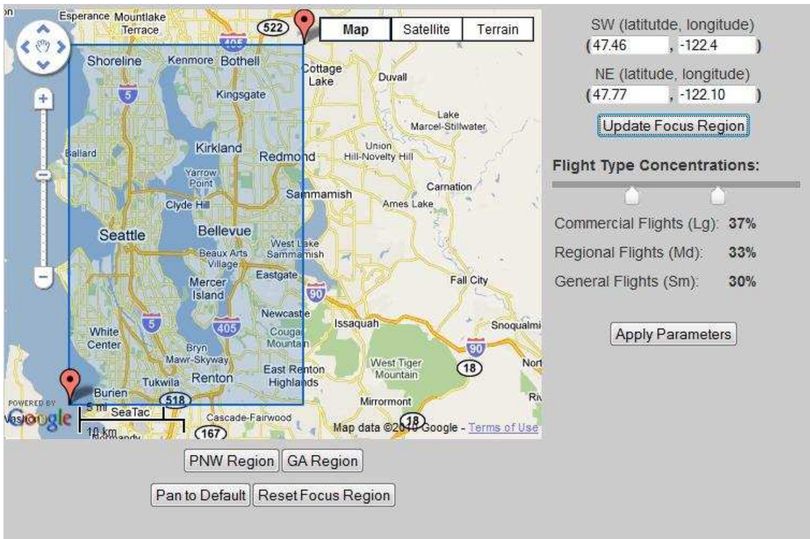
Operating Area +

Number of UA		4
Max Operating Altitude	f	3000
Min Operating Altitude	f	500
Total Flight Hours		11680
Operating Area	mi^2	299.1
Structure Density	bldg/mi^2	1270
Structure Size	ft^2	2000
Average Structure Height	ft	30
Structure Fatality Rate	deaths/strike	0.02
Average Pedestrian Density	people/mi^2	415
Pedestrian Fatality Rate	deaths/strike	0.5

Figure 5.13: Operating area properties in web-based risk calculator.

5.3.3 Transient Aircraft

The air traffic densities are automatically computed for the region selected with the automated map tool. Typically, at this low altitude range one would assume that the majority of air traffic is from general aviation. However, since the operation is taking place near sev-



SW (latitutde, longitude)
(47.46 , -122.4)
NE (latitude, longitude)
(47.77 , -122.10)

Flight Type Concentrations:

Commercial Flights (Lg): 37%
Regional Flights (Md): 33%
General Flights (Sm): 30%

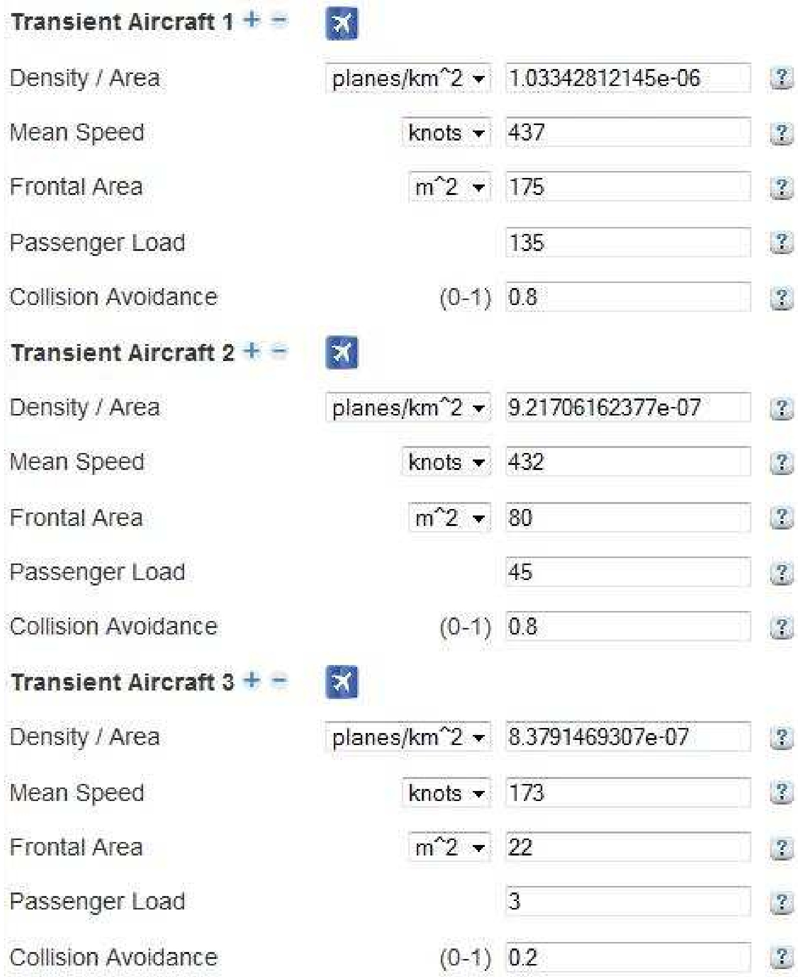
Figure 5.14: Automated air traffic tool.

eral airports, the default distribution (37% commercial jets, 30% regional jets, 33% general aviation) will still be used to model the air traffic. Figure 5.15 shows the transient aircraft models determined from the air traffic database.

The FAA will undoubtedly require any UAS operating so near a major airport to be equipped with transponders regardless of their operating altitude. Commercial and regional jets, which are equipped with TCAS, will then have the ability to reliably avoid a midair collision with the BAT 3. Collision avoidance should be conservative, however, since the BAT 3's small size will limit the ability of a transient aircraft pilot to see and avoid the aircraft. Collision avoidance of 80% will be assumed for commercial and regional jets and 20% for general aviation (Section 3.4 showed general aviation averages 36%).

5.3.4 Risk Assessment Results

The risk assessment results in an expectation of 7×10^{-8} midair collisions per UA flight hour (one every 1,223 years) and 1×10^{-5} pedestrian strikes per UA flight hour (one every nine years). Building strikes are expected to happen at a rate of 1×10^{-3} per UA flight hour or roughly one per month. These events result in 3×10^{-5} fatalities per UA flight hour



Transient Aircraft 1

Density / Area	planes/km^2	1.03342812145e-06
Mean Speed	knots	437
Frontal Area	m^2	175
Passenger Load		135
Collision Avoidance	(0-1)	0.8

Transient Aircraft 2

Density / Area	planes/km^2	9.21706162377e-07
Mean Speed	knots	432
Frontal Area	m^2	80
Passenger Load		45
Collision Avoidance	(0-1)	0.8

Transient Aircraft 3

Density / Area	planes/km^2	8.3791469307e-07
Mean Speed	knots	173
Frontal Area	m^2	22
Passenger Load		3
Collision Avoidance	(0-1)	0.2

Figure 5.15: Transient aircraft properties in web-based risk calculator.

or one fatality every three years. While a fatality expectation of this magnitude should be enough to raise flags about the operation, putting these incident rates into financial terms will make this result more tangible. If every fatality is covered by a \$10 million insurance policy, the price to insure the operation is \$333 per UA flight hour which gives an annual cost of about \$3,900,000 for the operation.

These costs clearly indicate that using UAS to monitor traffic in an urban context is not currently a safe or economically viable option. These expenses represent only the insurance risk from human safety, not UAS repair and replacement costs, property damage, and other general operational costs. Given the present state of UAS, other options such as manned aircraft or ground-based cameras are likely better options from financial and safety points of view.

Chapter 6

CONCLUSION

6.1 Summary

A risk model has been developed to estimate the risk from UAS operations to people aboard other aircraft and on the ground. The midair collision model is based on random collision theory with the addition of an effective collision avoidance factor. The collision model was validated by comparing actual and predicted collision rates for general aviation during two historical periods. The midair collision and ground strike models were used to build a risk assessment tool, which was implemented as a web-based application.

The necessary information on the UAS, the operating area and the transient air traffic is collected from the user. The risk associated with the operation is then calculated and presented to the user in terms of expected number of midair collisions, building strikes, pedestrian strikes and overall fatalities per UA flight hour. The human safety risk is also translated into economic terms based on a user-specified liability protection per fatality. This cost serves to give the user a tangible measure of the risk, since a cost per flight hour is easier to grasp than the expected number of fatalities per flight hour.

To allow flexibility in the type of operation the tool can be used to model, multiple operating areas may be included in a single risk calculation. Additionally, each operating area's air traffic can be comprised of multiple transient aircraft models. Predefined models for several categories of UAS and transient aircraft are provided to assist the user in performing quick estimates. A small database of air traffic information was compiled and made available on the website through an interactive map. This feature allows the user to specify the operating area (currently within two regions for which data has been collected) and have the majority of transient aircraft information filled in automatically. The long-term goal is to make automated air traffic data available for the entire NAS with the addition of several features to improve the accuracy.

A section of the website is dedicated to directing users to helpful resources for gathering the requested information. A user's guide is made available to explain any requested information that may be unclear as well as how the information can be obtained. Several example calculations are included on the website to exhibit how the tool should be applied to actual UAS operations. The example calculations also serve to demonstrate the type of operation for which the risk model is tailored. Although improvements to the risk model and to the website are planned, the first version of the web-based risk assessment tool is complete. As more data becomes available on UAS operations, it can be used to refine and validate the model.

6.2 Future Work

A functional version of the risk assessment tool is in place, but a number of improvements could be made. The following are potential changes to be explored for future improvement. Some represent relatively minor additions to improve the accuracy and flexibility of current functionality. Others are larger-scale changes that would actually expand the functionality beyond that of the current tool.

A risk assessment is currently limited to a single UAS model for the entire operation. The tool can be given even greater flexibility by allowing the calculation to accommodate multiple UAS models within a single operation. This feature would allow an operation that uses a team of heterogeneous UA to be represented more accurately. The user could also be given more freedom by having the option to calculate the required level of UAS reliability to meet a specified level of risk. Other variables, such as air traffic and population densities, could also be determined in place of the safety risk, which is useful in selecting an appropriate operating area.

At this early point in the domestic deployment of UAS, one can assume most UAS operations will not be near busy highways and roads. However, one purpose of this tool is to predict the risk of potential future operations in order to encourage the safe expansion of UAS utilization. Since many useful operations can be imagined in which UAS operate near or directly over automobile traffic, the operating area properties could be expanded to include information on roads and traffic in the region. One would simply treat the expected number of vehicles as small buildings in the current model, but this solution is less than ideal.

As previously mentioned, expanding the air traffic database is a simple way to significantly improve the tool's usefulness. Hopefully, automated air traffic data will eventually be available for the entire NAS. In addition to increasing the area covered, the depth of the historical data also needs to be improved. With a larger sampling of air traffic, additional filters can be used to improve the model's accuracy by matching items such as time of day, season/month of year and day of the week. Presently, the user must modify the default air traffic distribution between aircraft type based on the altitude range and their knowledge of traffic through the airspace. The raw data being gathered actually has the information necessary to assign 90% or more of the traffic to one of the transient aircraft models. The aircraft codes used by the data provider must be assigned to one of the three aircraft models so that the sorting algorithm is able to distinguish between type of aircraft and automatically set the distribution.

Section 3.4.2 discussed the comparison of historical bird strike data to predictions of the midair collision model. Cooperation with the Air Force Bird/Wildlife Aircraft Strike Hazard team may provide useful bird population data in the near future. If the model is able to produce a reliable approximation of bird strike frequency, the risk from bird strikes can be included explicitly in the model. This addition is preferable to grouping bird strikes into the overall mishap rate because, unlike many failures, the risk can change drastically between operations based on location, season and even time of day. This addition becomes especially important if a complete economic risk assessment is pursued.

As discussed in Section 2.2, lost-link procedures are an issue of importance in UAS airworthiness approval since most UAS rely heavily on a pilot communicating with the UA for high-level control, navigation and tasking. The current calculation accounts for the contribution to the overall crash rate from lost-links, but not the frequency of lost-links or the presence of a reliable programmed behavior. The risk model would have greater precision if communication losses were specified separately from the overall failure rate. Depending on variables such as terrain and weather, the frequency of lost-links may need to be adjusted from one operation to another. Allowing the user to fine-tune the reliability of the UAS's lost-link procedure allows advances in that area to be reflected in the risk assessment before they are seen in historical mishap rates.

In the absence of well designed lost-link procedures, an aircraft may wander and crash outside of the intended operating area or flight path. Since this event may bring the UA into regions of higher population density, the ground strike risk model would need to be reformulated. Instead of a static area with a constant population density, the surrounding area would better be represented by a series of concentric (or parallel) regions with an increasing probability of pedestrian and building strikes as one moves further away from the intended operating area or path. Conversely, the probability of a crash in each region decreases as one moves further away from the intended area or path.

Section 2.1 explains the purpose of this human safety risk assessment in comparison to other types of risks which could be considered. If one were so interested, the risk model can be adapted for calculating the overall economic risk including UA repair/replacement cost and property damage. Additional information would be collected as discussed in Sections 2.2 and 2.3, and the risk model would be reworked to differentiate between types of mishaps which incur different costs. The takeoff and landing phases would be separately considered since they suffer from a high number of mishaps which may not contribute to human safety risk. This type of assessment is currently considered to be outside the scope of the AFSL project.

The AFSL is working to establish relationships with other groups in industry and academia that have worked on related projects. Mutually beneficial cooperation will be pursued in hopes of further refining and expanding the capabilities of the AFSL risk assessment tool. Developing these relationships will also help to publicize the risk assessment website and generally promote a risk-based approach to UAS regulation.

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Appendix A

RISK ASSESSMENT USERS GUIDE

This guide is intended to step you through the process of finding and filling in the information needed for a risk calculation. Every operation will be different and some may take a little research and creativity to find the right data.

A.1 UAS Properties

For the most part, this is information you should already have or can easily obtain.

Mean Speed - Average operating speed of the UA, not necessarily max.

Frontal Area - Approximate area of the UA when viewed from the front. Calculate by considering a series of rectangles enclosing portions of the aircraft. For example, two long narrow rectangles enclosing the wings, one rectangle enclosing the fuselage and smaller additions to cover tail pieces, wing-mounted engines, etc.

Wingspan - Umm. . . yeah.

Length - Distance from tip to tail of UA.

Glide Angle - What is the best glide angle the UA could maintain without power? Glide angle is the arctangent of D/L (or $90^\circ - \tan^{-1}(\mathrm{L/D})$).

Failure Rate - How many times per flight hour does the UA crash (for any reason, including operator error, other than midair collision). If takeoff and landing will take place in a restricted, pedestrian free area, the failure rate should not include takeoff and landing mishaps, since they pose no threat to public safety. The failure rate must be based on actual flight history.

General Collision Avoidance - If the UAS has any sense and avoid ability, how effective is it at detecting, tracking and maneuvering to avoid *non-cooperative* aircraft. A value of 1 represents perfect avoidance and a value of 0 represents no avoidance capability.

In-fleet Collision Avoidance - When two or more UA within a team have conflicting flight paths, how effectively can they avoid a collision (the avoidance can be centralized or distributed). A value of 1 represents perfect avoidance and a value of 0 represents no avoidance capability.

A.2 Operating Areas

If the UA will operate over very diverse areas (with respect to ground population and air traffic), you may choose to use multiple operating area models. Simply click the plus sign next to Operating Area 1 to add another operating area. If you wish to remove a particular operating area simply click the minus sign next to that operating area.

Although the calculation is best suited for operations in which the UA patrol a static region, it can certainly be used for a variety of mission profiles. In the case of a long distance flight from one location to another, the operating area is represented by a swath of airspace along the flight path. The width of the swath will depend on how closely the UAS is capable of tracking waypoints and how far off course the UA could potentially crash, which depends on its glide angle and operating altitude. Generally a width in the range of 1-10km is appropriate. If the air traffic and ground population do not vary too widely over the flight path, then the region could be considered as a single operating area. If the UA will pass through highly disparate areas, then you may choose to consider the flight path as several different operating areas with uniquely defined population and air traffic densities.

Once you have chosen how many operating areas your calculation will require, the following information is needed.

Number of UA - How many UA will be used simultaneously in the operating area (on average).

Max Operating Altitude - Highest altitude any UA will reach over the operating area.

Min Operating Altitude - Lowest altitude any UA will reach over the operating area excluding launch & retrieval. [1]

Total Flight Hours - Between all the UA, how many flight hours the operation will require over the operating area. For example, an operation in which 4 UA fly for 10 hours and 2 UA fly for 20 hours, the total is 80 flight hours.

Structure Density - On average, how many buildings per unit area are in the operating area.

Structure Size - Average size (area footprint) of buildings in the operating space.

Structure Height - Average height of buildings in the operating space. Clearly the height of buildings with larger area footprints should be more heavily weighted.

Structure Fatality Rate - How many fatalities are expected from a UA striking an average building. This rate depends on how densely the buildings are populated during the operation, how sturdy the buildings are and how large/heavy/frangible the UA is. Many small UA pose essentially no threat to anyone indoors, while a 10,000kg Global Hawk poses a very serious threat.

Average Pedestrian Density - How many pedestrians per unit area will be outside in the operating area during operation (exposed population). See additional comments in the Resources section below.

Pedestrian Fatality Rate - If a pedestrian is struck by the UA, how likely is a fatality. This rate will depend on the size, weight and frangibility of the UA. Frangibility means how easily the aircraft is broken. A highly frangible UA is much less likely to kill or seriously injure a person because it would easily break apart during a collision.

---

[1] Min and Max altitudes should allow some buffer space and the altitude range (max altitude - min altitude) should be at least half a kilometer.

A.3 Transient Aircraft

The air traffic through the operating space is modeled by a few representative aircraft. We recommend using a single model to represent a class of aircraft. Multiple aircraft models can be applied to a single operating area to give a more accurate estimation. Pre-defined models are available for three categories of aircraft: commercial jets, regional jets and small aircraft. If multiple operating areas are being used, then be sure to specify the areas in which you wish to include each transient aircraft model. A model may be applied to a single area, all areas or a subset of the operating areas. You will need to provide the following information on the transient aircraft models.

Density/Area - How many aircraft (in this category) per unit area are expected to be in the operating space during operation. This number should only include aircraft expected to be within the UAs altitude range. See more in the Resources section below.

Mean Speed - Average cruising speed (not max) of transient aircraft.

Frontal Area - Approximate area of the transient aircraft when viewed from the front. See comments on UA frontal area for how to estimate.

Passenger Load - How many people are onboard the average aircraft in this category.

If your operating area is in the Northwest U.S. (ID, OR, WA & Western MT) or central Georgia, the website can automatically extract air traffic density figures based on a historical sampling. We hope to add this capability for the rest of U.S. airspace as well. To use this feature, click the "Show Map" tab along the right hand side of the calculation page. You can then select your operating area (within the northwest) by dragging the two corners of the selection box on the map. If you know the latitude and longitude of the corners, you may also specify them directly and click "Update Focus Region" to update the map. If you have multiple operating areas, select which one you wish to model (you can use the map tool to model each operating area but only one at a time). The historical data being sampled currently can only give the total air traffic without regard to aircraft type. The default setting is to model the air traffic as 30% general aviation (small), 33% regional jets (mid-size) and 37% commercial jets (large). The user may move two sliders along a bar to modify the distribution between aircraft type if they have more specific knowledge of the type of air traffic through the region. Once everything is set to the correct values, click "Apply Parameters" to produce the appropriate transient aircraft models and determine the size of the operating area. Any existing transient aircraft models that are only applied to the operating area being modeled will be replaced by the automatically generated models. Any existing transient aircraft models that apply to other operating areas will not be affected regardless of whether they apply to the area being modeled.

A.4 Insurance Coverage

For most users, being told that 2E-8 midair collisions or 1E-7 fatalities per flight hour are expected may not be very meaningful. Although doing so may sound insensitive, the best way to ensure public safety is to translate these figures into economic terms so the average user can make an informed decision. This cost will allow businesses, universities and government/military bodies to quickly know whether or not a proposed operation is safe based on the cost to insure the human safety risk. This cost will depend on how much coverage is deemed necessary, so selecting a sufficiently large amount to represent the gravity of human safety is important. A separate economic risk assessment considering additional factors (e.g. UA repair, property damage, etc.) would be necessary to determine the overall insurance risk. The result of this risk assessment only indicates the danger to the public.

Liability/Person - How much liability coverage do you want per fatality caused.

A.5 Resources

A.5.1 Buildings

We recommend using online services such as Google Earth or Google Maps to view satellite imagery of the operating area. These tools, combined with some knowledge of the area, will allow you to estimate the structure density, size, height and fatality rate. The U.S. Census

Bureau (see below) publishes some data on the density of housing units per area, which may be useful (the housing unit data is included when the results are viewed in tables but not in the map view).

This portion of the calculation could also be used to represent objects, such as large boats, which offer some protection to the people inside. If the proposed operation is over a very sparsely populated area this factor may be negligible.

A.5.2 Population

The satellite imagery tools mentioned above can also be useful in determining how densely the operating area is populated. The Census Bureau Population Finder provides the best information we have found on population density. Keep in mind that the given populations are based on residency and may change for urban areas depending on the time of day. The highest resolution data is by 5 digit zip codes and may be limited for sparsely populated areas. Remember that you want the exposed population, not the total population. Knowing what portion of the total population should be considered exposed will require some knowledge of the area over which you want to operate. The same goes for information on structures in the operating space. Do not rely solely on information from online resources.

A.5.3 Air Traffic

Since truly predicting the air traffic through non-restricted air space is nearly impossible (especially more than a day in advance), this information should be based on historical data. In addition to considering traffic over the 2D space, the operating altitude range should also be considered. This differentiation is very important as predefined altitude windows are a primary means of separating different type of air traffic. A UAS operating below FL100 and not near any airports/airfields, for instance, does not pose a threat to commercial airliners. Because typical air traffic changes drastically throughout the course of a day, the time of day should also be considered if the UA will only be in flight for part of the day.

During the day about 5,000 planes are over the US at once, which gives 5.09e-4 aircraft/km^2. However, much of this traffic is concentrated near airports and major airways and most will be in Class A airspace, between FL 180-FL600 (roughly 5.5km-12.3km), except near airports. The best way to determine air traffic in the area of interest is with services available from websites like FlightAware.com and FlightExplorer.com. For $10/month Flight Explorer offers a personal edition (requires downloading their software) which allows you to zoom into a specific area and monitor current traffic including the aircraft type and altitude. Check the number of aircraft in the proposed operating area during the timerange in which you intend to operate. Gathering this data over a few days (although longer is obviously better) will give you an idea of the air traffic density. This tool is probably the best combination of accuracy and affordability currently available.

Examining aeronautical charts (high and low altitude) for the region may help in finding an area where little air traffic is expected. Current charts may be viewed free of charge at SkyVector.com and may be purchased in hard and soft copy from the FAA National Aeronautical Charting Office. Examining these charts can help give you an idea of where the air traffic may be concentrated. However, you must consider that some routes are used far more than others and not all air traffic flies on charted routes, which means that even if no charted routes pass through the operating area, aircraft may still pass through.

Once the air traffic density has been determined (including altitude considerations), models must be selected for the transient aircraft. Several default aircraft models may be selected in the calculation or you may use your own models for transient aircraft. Aircraft specifications may be found at websites such as PlaneandPilotMag.com (lots of info for smaller planes), FlyAOW.com (limited info for commercial planes), aircraft manufacturer websites and resources like Wikipedia.

Appendix B

AIR TRAFFIC CODE

Below is the Matlab code used to determine the air traffic density for a 3D region specified by the user. The air traffic data is loaded from some database (in this case simply an Excel spreadsheet) and then processed using some implementation of this routine. For the website the data is stored in MySQL and processed using the following routine translated into PHP.

```
% AFSL Risk Assessment Tool
% Air Traffic Density Calculation

% This routine calculates the air traffic density for a 3D region defined
% by a latitude/longitude box and altitude range. The time range of
% interest may also be specified.

close all
clear
clc

%% Variables to be read from website user input
East=-112;  % Eastern longitude boundary (Deg E = positive, Deg W = negative)
West=-114;  % Western longitude boundary
North=49;   % Northern latitude boundary (Deg N = positive, Deg S = negative)
South=47;   % Southern latitude boundary
maxAlt=5;    %Max Alititude in km
minAlt=1;    %Min Altitude in km
timestart=6; %time of day to start operation (24.0 PST)
timeend=24;   %time of day to end operation (24.0 PST)

%% End user variables, begin main routine

maxAlt=maxAlt*32.8084; %convert to 100ft (flight level)
minAlt=minAlt*32.8084;  %convert to 100ft (flight level)
```

```
%Read air traffic data from excel spreadsheet
data=xlsread('FlightData_3210.xlsx'); %(Alt, Long, Lat, Time)
[m,n]=size(data);

hours=0;
firstday=data(1,4)/86400-.25;
firsttime=24*(firstday-floor(firstday));
if firsttime<timeend
    if firsttime<timestart
        hours=hours+(timeend-timestart);
    else
        hours=hours+(timeend-firsttime);
    end
end

lastday=max(data(:,4))/86400-.25;
lasttime=24*(lastday-floor(lastday));
if lasttime>timestart
    if lasttime>timeend
        hours=hours+(timeend-timestart);
    else
        hours=hours+(lasttime-timestart);
    end
end

middledays=floor(lastday)-floor(firstday)-1;
if middledays>0
    hours=hours+middledays*(timeend-timestart);
end

%Check if each aircraft is in the specified lat/long box, altitude range and timerange
count=0;
for k=1:m
    if (data(k,1)<=maxAlt) && (data(k,1)>=minAlt) && (data(k,2)>=West) &&...
  (data(k,2)<=East) && (data(k,3)<=North) && (data(k,3)>=South)
```

```
        days=data(k,4)/86400-.25;
        time=24*(days-floor(days));
        if (time<=timeend) && (time>=timestart)
            count=count+1;
        end
    end
end

%Average air traffic over collection time and adjust to per unit area
traffic=count/hours;
a=6378; b=6357;
phi=mean([North South]);
Re=sqrt(((a^2*cos(phi))^2+(b^2*sin(phi))^2)/((a*cos(phi))^2+(b*sin(phi))^2));
area = pi/180*Re^2*abs(sin(South*pi/180)-sin(North*pi/180))*abs(East-West);
density=traffic/area;
disp(['The average air traffic density over the operating area is ', num2str(density),...
    ' aircraft/km^2'])
disp(['The size of the operating area is ', num2str(area), ' km^2'])
```

Appendix C

TRAFFIC DENSITY MAPPING CODE

Below is the Matlab code used to map the air traffic density over the operating area specified by the user. The air traffic data is loaded from a database and then sorted into a grid defined by the user. The grid divides the operating area into sections of a set longitudinal width and latitudinal height. Parts of the operating area that pose the highest risk of midair collision can then be avoided

```
% AFSL Risk Assessment Tool
% Air Traffic Density Mapping

% This routine maps the air traffic density for a 3D region defined
% by a latitude/longitude box and altitude range. The time range of
% interest may also be specified.

close all
clear
clc

%% Variables to be read from website user input
dlat=.2;    % element latitude height (must be positive)
dlong=-.2;  % element longitude width (must be negative)
East=-117;  % Eastern longitude boundary
West=-122;  % Western longitude boundary
North=49;   % Northern latitude boundary
South=48;   % Southern latitude boundary
nlat=(North-South)/dlat;
nlong=(West-East)/dlong;

maxAlt=10;    %Max Alititude in km
minAlt=1;    %Min Altitude in km
timestart=6; %time of day to start operation (24.0 PST)
timeend=24;   %time of day to end operation (24.0 PST)
```

```
%% End user variables, begin main routine

maxAlt=maxAlt*32.8084; %convert to 100ft (flight level)
minAlt=minAlt*32.8084;  %convert to 100ft (flight level)

%Initializations
Results=zeros(nlat,nlong);
ResultsHigh=zeros(nlat,nlong);
ResultsLow=zeros(nlat,nlong);
areas=zeros(nlat,1);

%Read air traffic data from excel spreadsheet
data=xlsread('FlightData_3210.xlsx'); %(Alt, Long, Lat, Time)
[m,n]=size(data);

%%
%For each aircraft in the log, assign it to the corresponding element in
%the Results matrix if in correct lat/long/alt region and timerange
for k=1:m
    if (data(k,1)<=maxAlt) && (data(k,1)>=minAlt) && (data(k,2)>=West) && (data(k,2)<=East)...
            && (data(k,3)<=North) && (data(k,3)>=South)

        days=data(k,4)/86400-.25;
        time=24*(days-floor(days));
        if (time<=timeend) && (time>=timestart)
            alt=data(k,1);
            long=data(k,2);
            lat=data(k,3);
            j=ceil((lat-South)/dlat);
            if j==0
                j=1;
            end
            i=ceil((West-long)/dlong);
            if i==0
                i=1;
```

```
            end
            Results(j,i)=Results(j,i)+1;

            %Keep separate log of aircraft above/below FL180
            if alt<180
                ResultsLow(j,i)=ResultsLow(j,i)+1;
            elseif alt>=180
                ResultsHigh(j,i)=ResultsHigh(j,i)+1;
            end
        end
    end
end

%% Adjust Results for area and time

%Compute area of each mesh element and adjust Results to be per km^2. Area
%will only vary with latitude so data can be adjusted by row.
a=6378; b=6357;
for k = 1:nlat
    phi=South+(k-.5)*dlat;
    Re=sqrt(((a^2*cos(phi))^2+(b^2*sin(phi))^2)/((a*cos(phi))^2+(b*sin(phi))^2));
    areas(k)= pi/180*Re^2*abs(sin((South+(k-1)*dlat)*pi/180)-sin((South+k*dlat)
*pi/180))*abs(dlong);
    Results(k,:)=Results(k,:)./areas(k);
    ResultsHigh(k,:)=ResultsHigh(k,:)./areas(k);
    ResultsLow(k,:)=ResultsLow(k,:)./areas(k);
end

% Calculate how many hours of data in the specified timerange are used
hours=0;
firstday=data(1,4)/86400-.25;
firsttime=24*(firstday-floor(firstday));
if firsttime<timeend
    if firsttime<timestart
        hours=hours+(timeend-timestart);
    else
```

```
        hours=hours+(timeend-firsttime);
    end
end

lastday=max(data(:,4))/86400-.25;
lasttime=24*(lastday-floor(lastday));
if lasttime>timestart
    if lasttime>timeend
        hours=hours+(timeend-timestart);
    else
        hours=hours+(lasttime-timestart);
    end
end

middledays=floor(lastday)-floor(firstday)-1;
if middledays>0
    hours=hours+middledays*(timeend-timestart);
end

%Convert results from totals to aircraft at one time (timestart-timeend)
Results=Results./hours;
ResultsHigh=ResultsHigh./hours;
ResultsLow=ResultsLow./hours;

%% Construct Mesh Elements and assign corresponding traffic from Results matrix

mesh=struct('Geometry', {},'BoundingBox', [],'Lon',[],'Lat',[],'Element',{},'AircraftCount',[]);
for k=1:(nlat*nlong)
    j=ceil(k/nlong);    %row of Results being represented
    i=k-(j-1)*nlong;    %column of Results being represented
    latN=South+j*dlat;
    latS=latN-dlat;
    longE=West-i*dlong;
    longW=longE+dlong;
    mesh(k,1)=struct('Geometry',{'Polygon'},'BoundingBox',[longW latS; longE latN],'Lon',...
[longW longE longE longW longW NaN],'Lat',[latN latN latS latS latN NaN],'Element',...
```

```
{k},'AircraftCount',[]);
    mesh(k,1).AircraftCount = Results(j,i);
end

%% Make Plots
figure
title('Map of Air Traffic Density in NW Airspace - Aircraft/km^2')
axesm('MapProjection', 'eqaconic', 'MapParallels', [], 'MapLatLimit', [South-2*dlat North...
+2*dlat], 'MapLonLimit', [West+2*dlong East-2*dlong], 'MLabelLocation', dlong*2,...
'MLabelParallel', 'south', 'PLabelLocation', dlat*2,'MeridianLabel', 'on',...
'ParallelLabel', 'on', 'GLineStyle', '-', 'GColor' , 0*[1 1 1], 'GLineWidth',.5,...
'Grid', 'on', 'Frame', 'off')

states = shaperead('usastatehi', 'UseGeoCoords', true);
geoshow(states, 'DisplayType', 'polygon','FaceColor', [1 1 1], 'LineWidth',2)
hold on

mincount=min([mesh.AircraftCount]);
maxcount=max([mesh.AircraftCount]);
surfaceColors = makesymbolspec('Polygon', {'AircraftCount', [mincount maxcount],...
'FaceColor', cool(numel(mesh))});
geoshow(mesh, 'DisplayType', 'polygon','SymbolSpec', surfaceColors)
caxis([mincount maxcount])
colormap('cool')
colorbar

%Construct matrices of x(long) and y(lat) coordinates corresponding to Results matrix
x=[West-dlong/2:-dlong:East+dlong/2];
X=ones(nlat,nlong)*diag(x);
y=[South+dlat/2:dlat:North-dlat/2];
Y=(ones(nlong,nlat)*diag(y))';

figure
plot(states(47).Lon,states(47).Lat,'r-', 'LineWidth',1.5); hold on
plot(states(37).Lon,states(37).Lat,'r-', 'LineWidth',1.5)
plot(states(26).Lon,states(26).Lat,'r-', 'LineWidth',1.5)
```

```
plot(states(12).Lon,states(12).Lat,'r-', 'LineWidth',1.5)
contour(X,Y,Results,60);
axis('equal')
ylim([South-dlat North+dlat])
xlim([West+dlong East-dlong])
title('Contour Plot of Air Traffic in NW Airpsace - Aircraft/km^2')
xlabel('Longitude - ^{o} West')
ylabel('Latitude - ^{o} North')
zlabel('A/C per km^{2}')
caxis([0 maxcount])
colormap('jet')
colorbar

figure
surf(X,Y,Results)
title('Surface Plot of Air Traffic in NW Airpsace')
xlabel('Longitude - ^{o} West')
ylabel('Latitude - ^{o} North')
zlabel('A/C per km^{2}')
```