Integration of Unmanned Aviation Systems within the National Airspace System: A Multi-Objective Risk Management Approach

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Abstract

The future of the National Airspace System (NAS) managed by the Federal Aviation Administration (FAA) will see a major increase in the proliferation of unmanned aviation systems (UAS) as the technologies for those systems advance, new uses are discovered. At the same time, new rules under the Next Generation (NextGen) NAS modernization program will include new methods of air traffic management relying on the Global Positioning System (GPS) and a more efficient flight management concept called Trajectory Based Operations (TBO). The FAA must develop the new airspace rules and procedures to enable full integration of UAS into airspace previously reserved for manned aircraft only. These policies must balance growth in UAS use over time with a need to maintain safety, as well as continuing to ensure efficiency for traditional aviation operations. Lack of capabilities like "see and avoid" and volatility in the controllability of UAS contribute significantly to concerns about the safety of UAS integration. Presently, airspace rules for UAS that do not meet NAS airworthiness standards do accommodate some use by requiring extremely large safety separation intervals from manned aircraft, achieved through the use of exclusive Special Activity Airspace (SAA) which in turn reduces airspace efficiency for other NAS users. Linking safety and efficiency through the configuration and separation intervals between aircraft frames the UAS integration as a competing multiple objectives problem, which previous models have not directly considered. This thesis presents a methodological framework for assessing optimal tradeoffs between multiple NAS objectives from the key system state and input variables in terms of available risk management options. By understanding these optimal tradeoffs, the FAA can develop new risk management strategies for integrating UAS which remain non-inferior in consideration of efficiency objectives. The methodology remains applicable even when more objectives are added to the system.

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1. Introduction.

1.1. Problem Definition

The FAA is continuing long term work toward maturing the Concept of Operations (CONOPS) for integration of unmanned aviation systems (UAS) into the National Airspace System (NAS) [Hunt, 2013]. System integrators from the FAA have identified the current use of Certificates of Authorization or Waiver (COA) to allow special-purpose use of UAS by public agencies as one of the obstacles to integration. The current practice of accommodation through the use of special activity airspace (SAA) is not scalable to increased demand as the number of users and applications for UAS increases, and therefore does not meet expectations for full integration. Also, the use of any special activity airspace, including restricted airspace, decreases the overall efficiency of the NAS, contrary to the FAA mission, and especially under CONOPS that depend on Performance-Based Navigation (PBN) and Trajectory-Based Operations (TBO). Similar challenges exist for civil aviation operation of UAS under Special Air Worthiness Certificate policies.

Certain special-purpose UAS operations such as border surveillance, wildlife surveys, etc., are subject to greater levels of mission volatility (a measure of the degree and frequency of deviation from planned flight paths) compared to traditional flight modes: operators may need to make short notice changes to planned routes to track a moving subject on the ground, or they may require extended loiter around a stationary point of interest. The capacity of the operators, air traffic controllers (ATC), and the Air Traffic Management System (ATMS) to forecast and react to flight plan deviations, update 4-dimensional trajectories (4DT), and alert/alter the paths of other airspace users are states of the system, in addition to information about the current set of aircraft in the airspace.

Developing CONOPS for integrating UAS into the NAS may include ending the use of COAs and restricted airspace, and including them into systems that are based on TBO [Hunt, 2013]. However, the possibly high volatility in mission and other state information for common UAS uses poses challenges to ensuring safety if the capacity to react to that volatility is limited by factors such as technology or pilot and ATC workload. The greater the time required to react to changes in trajectory, the more buffer (in space or time) is needed around UAS to minimize risk.

In order to create and implement effective integration strategies, the FAA must consider multiple competing objectives, including NAS safety and efficiency. Evaluating tradeoffs directly could imply that there are times when policy makers would choose reduced safety in order to gain efficiency. To remove this obstacle, an acceptable methodology should instead consider the tradeoffs for system objectives like efficiency against risk management options.

1.2. General Approach and Risk Analysis Methodology

This thesis will emphasize a holistic, systems-based philosophy in developing a risk assessment, associated management strategies, and in communicating the results in a way that supports further maturation of the TBO CONOPS. In performing the risk analysis we will build a framework that is cognizant of the following realities which affect all complex systems as discussed by Haimes [2012]:

- "The Evolving Base," which connotes dynamic shifting rules and realities. For example: (a) Goals and objectives; (b) Stakeholders, policy makers, and interest groups; (c) Organizational, political, and budgetary baselines; (d) Advancing technological capabilities; and (e) Requirements, specifications, missions, users, and functions.
- "Emergent Forced Changes," which connote trends in external or internal sources of risk that may adversely affect specific states of the system. For the UAS integration in the TBO

example: any manifestation of volatility in trajectory may be the result of a forced change, or more broadly, a forced change may result from changes in the evolving base.

The holistic modeling approach to identifying risk in the UAS integration for TBO CONOPS can address multiple perspectives to capture the themes above, including but not limited to:

- Functional/mission
- Geo-spatial/geographic
- Temporal
- Environmental
- Operators/controllers
- Regulatory/legal

1.3. Focus of Thesis

While initially adhering to the tenets of holism in identifying sources of risk and associated risk management options, the thesis will ultimately focus on a smaller subset of critical sources of risk and management options associated with UAS in specific scenarios in Class A and E airspace relating to mission volatility of UAS. From that subset of specific scenarios, the thesis will develop a methodological framework that can be scaled to apply to risks from scenario volatility generally. Subsequent work using a similar framework could then be used to examine the other types of volatility such as from weather and atmospheric conditions.

1.4. Goals and Objectives

Develop a systems-based methodological framework for assessing risk in relation to multiple objectives in order to effectively communicate the trade-offs between airspace efficiency and risk under Trajectory-Based Operations (TBO), and propose risk management strategies to incorporate into the CONOPS. Answer the two policy questions: “what should we do/not do,” and “what are the impacts of current decisions on future options?” Policy makers employing the methodology will be able to:

1. Determine a subset of applicable scenarios for potentially replacing COA/restricted airspace for publicly operated UAS with TBO, which account for the most critical sources of risk.
2. Develop specific metrics with which to measure efficiency and safety objectives.
3. Describe tradeoffs in efficiency and safety objectives under scenarios for TBO CONOPS under consideration.
4. Identify possible impacts of current policy decisions on other objectives for the NextGen NAS given uncertainties in an “evolving base.”

2. Background and Literature Review

2.1. NextGen and UAS Concepts

2.1.1. NextGen Overview.

The problem of integrating UAS into the NAS has been included as part of a much larger modernization problem undertaken by the FAA. The broad goals of the modernization include improvements in sustainability, flexibility, and safety, as well as minimizing negative economic impacts [FAA, 2013]. Planning began in 2003, with formal implementation of the project starting in 2012, and an expected completion in 2025. The project is a complete systematic overhaul of the NAS, which had not been changed fundamentally since its inception decades ago. Many of the specific improvement programs are designed to use newer and emerging technologies, in particular with regard to navigation and air traffic management. Real-time information from Global Positioning System (GPS) satellites will replace radar as a primary means of reporting current locations for aircraft; Automatic Dependent Surveillance-Broadcast (ADS-B) and associated systems will report location and other flight information in real time between aircraft and controllers; and new automation systems will help manage all the data. The project also implements new concepts of flight planning and traffic management enabled by those new technologies, such as Performance Based Navigation (PBN) and several others which will allow for shorter flight paths, reduced delays, and reduced costs. Trajectory Based Operations is related to PBN and is also an operational improvement program within NextGen. As a result of the expected increased application for UAS in the NAS, NextGen planning has also included concepts for integrating UAS, but the requirement to fully integrate all types of UAS was formalized in the "FAA Modernization and Reform Act of 2012" passed by Congress and signed into law [FAA, 2012], making it a part of the larger NextGen project. Taken as a whole the NextGen represents a complex system of systems with many subsystems, components, and stakeholders, connected through multiple shared states and multiple objectives (many of them competing) [Haimes, 2013].

2.1.2. UAS Accommodation.

Prior to full implementation of NextGen, UAS operations have been (and continue to be) allowed under very limited conditions, primarily for research and development purposes, or for certain government uses; virtually no commercial uses are authorized (other than for R&D). Recent rules have taken effect that allow certain classes of small UAS to fly within operator line of sight without requesting COA/waivers [FAA, 2013]. The process by which UAS operators have been granted permission to operate in the NAS has been referred to as “accommodation” since it requires changes to normal flight operations for a particular segment of airspace. The biggest impact of UAS accommodation is that it typically requires air traffic controllers to restrict large segments of airspace from entry by other aircraft because of safety concerns. As a result, most UAS operations must occur in more remote areas, away from other manned flights, or risk being denied if the impact of restricting an airspace segment is deemed disruptive to other flights. As described earlier, this method of accommodation is not scalable to increased demand for UAS operations, especially in airspace segments where manned flights routinely operate such as urban areas, near airports, etc.

2.1.3. Classes of Airspace.

In the United States, the NAS is subdivided into six classes of airspace, denoted by the letters A, B, C, D, E, and G, each of which has specific rules for the types of aircraft allowed to enter and operate [FAA, 2008]. Classes B, C, and D of airspace are established around large, medium, and small airports, respectively. Rules for these airspace classes vary, but primarily they are established to control aircraft during the takeoff and approach phases of flight. Class G airspace is uncontrolled airspace mostly up to 1,200 feet altitude, and primarily used by smaller manned aircraft. Class A airspace is established primarily above 18,000 feet altitude, and primary users of class A airspace are aircraft in the cruising phase of flight. One of the distinguishing features for this class is the requirement to be under instrument flight rules (IFR) at all times. Class E airspace is controlled airspace generally between low level class G and class A areas, but it also includes very high altitudes above 60,000 feet. This thesis is primarily concerned with risk scenarios occurring in classes A and E airspace since these are ATC-controlled airspaces where UAS and manned aircraft are most likely to interact while performing their primary missions or functions and operating under TBO CONOPS.

2.1.4. UAS Types and Missions.

The Department of Defense was an early pioneer in the field of unmanned aircraft, so many of the classifications for UAS types and functions are reflected in that history [DoD, 2011]. First it is important to distinguish between the aircraft itself, called an unmanned aerial vehicle (UAV) or remotely piloted vehicle (RPV), and the unmanned aviation system as a whole, which also includes the associated ground control station (GCS), operators, and other interfaces with the NAS. In practice the terms are often used interchangeably. Distinctions among UAS have primarily focused on the size of the UAV and the typical operating altitude; military systems fall into one of five groups, ranging from hand-launchable to large systems, often armed or able to carry heavy payloads. Classifications can also be made based on propulsion types or other characteristics like fixed or rotary wing, etc. The FAA has classified small UAS as those up to 25lbs, which are covered under new line of sight rules as of November, 2013 [FAA, 2013].

2.1.5. Trajectory-Based vs. Clearance-Based Operations, and Airspace Efficiency.

The development of plans for TBO is a part of the FAA's NextGen NAS CONOPS to replace the current system of clearance-based operations [FAA, 2013]. The current clearance-based CONOPS is very intensive on air traffic controllers and does not take full advantage of existing and emerging technologies that can report and predict the trajectories of aircraft in flight in near real-time. This is particularly true for the cruising phase of flight (typically occurring in Class A, E, or oceanic airspace). In the nominal case, TBO will allow aircraft operators to submit flight plans and periodically make en route updates based on changes to flight parameters (wind, weather, etc.) [JPDO, 2011]. The flight plans and updates would be managed by an automated system supervised by ATC which could identify conflicting routes well in advance and alert operators (via ATC instructions) to take corrective actions.

Apart from improving the quality and efficiency of ATC functions, TBO also has the potential to improve airspace efficiency by enabling performance-based navigation (PBN), another major desired outcome of NextGen [FAA, 2013]. The majority of current flights in Class A, E, and oceanic controlled airspace are point-to-point flights following "straight" line paths. These flight paths are relatively easy to track and predict even given variances in speeds, wind effects, etc., and thus should be relatively easy to deconflict under a TBO CONOPS given periodic and near-real-time updates.

In cases where public agencies currently perform limited UAS operations under clearance-based operations, the FAA issues COAs, and ATC accordingly sets aside large sections of restricted airspace within which the UAS may operate and no other aircraft may enter [FAA, 2013]. These large sections of restricted airspace are inefficient since they may span a width of many miles, causing a costly rerouting of other air traffic far from optimal paths. This rerouting occurs regardless of whether the UAS is actually in the vicinity of another potential flight path at the time of crossing.

With TBO, there is a potential to make more efficient use of that airspace by clearing air traffic routes through a UAS's operating area as long as they do not conflict with the UAS trajectory in 4D [JPDO, 2011]. In other words, with knowledge of the intended future locations of UAS, airspace can be more open, and ATC may not need to block off such large restricted areas, as long as there is a capacity to track and react to changes in UAS trajectory. However, there are tradeoffs among multiple sources of risk associated with all available decisions and policy options. Understanding these risks and the associated tradeoffs will be critical to making decisions about the proper employment of TBO CONOPS with UAS.

2.1.6. Anticipated Mission Volatility in UAS Operations.

Meanwhile, the integration of UAS within the NAS is expected to enable a significant expansion of UAS applications (especially for public safety, national security, and science), which are fundamentally different from point-to-point services such as mentioned above [FAA, 2013]. Such uses for UAS are expected to include surveillance of large areas (such as along the southern border) and long period atmospheric monitoring. Both applications differ from traditional flight operations in that the aircraft is likely not to follow a shortest path between two points, rather it may fly a repeating pattern that covers a large ground area. Furthermore, several factors may affect the UAS's likelihood of following an exactly preplanned route—longer flight times or weather conditions resulting in greater drifting from planned trajectories in time or space, among others. While not insignificant, those factors may be accounted for as variance in models that predict 4D trajectories.

More significant to operators and ATC is the mission volatility of UAS. For example, a UAS conducting border surveillance may need to break from its search pattern and track a particular identified target. The likelihood of identifying targets, the tracking routes, and durations are all subject to uncertainty that and cannot be predicted in a submitted flight plan. Therefore accounting for the uncertainty in mission volatility requires a measurement of the human and technological factors that affect the ability of operators and ATC to react to changes.

2.2. Tools for Analysis

2.2.1. Fractile Method and Triangle Distributions.

The models developed in this thesis represent our understanding of the tradeoffs among the multiple objectives associated with NextGen, so it is imperative that we also acquire or "develop" an appropriate database with which to populate our model and to generate results and solutions that are representative and meaningful. Our limited experience (if at all) in redesigning the NAS into efficient corridors and integrating UAS within it implies that no historical data is available to perform this task. Therefore in this thesis we are building on two established and effective methodologies through which to generate representative databases by soliciting the evidence from experts: the fractile method and triangle distribution [Haimes, 2009].

The fractile method is based on the idea that a cumulative density function (CDF) for an event random event X is the nonexceedance probability of x [Haimes, 2009], where

$$\text{CDF: } P(x) = prob[X \leq x]$$

The method constructs a CDF by partitioning the cumulative probability axis into four equal sections divided at the 25th percentile, the median, and the 75th percentile. In considering risk of UAS integration, the random variable X may represent the number of incidents that will occur per million (10^6) flights of UAS operations under a particular scenario. For this example, consider in the best case experts say there are no incidents; in the worst case there are 10 per 10^6. They also believe the median number of incidents will be three, and that half of the time the number of incidents will be within one of the median. To compute the fractile method, these estimates mean:

$$P(0\ incidents) = 0,$$
$$P(2\ incidents) = 0.25,$$
$$P(3\ incidents) = 0.5,$$
$$P(4\ incidents) = 0.75,$$
$$P(10\ incidents) = 1$$

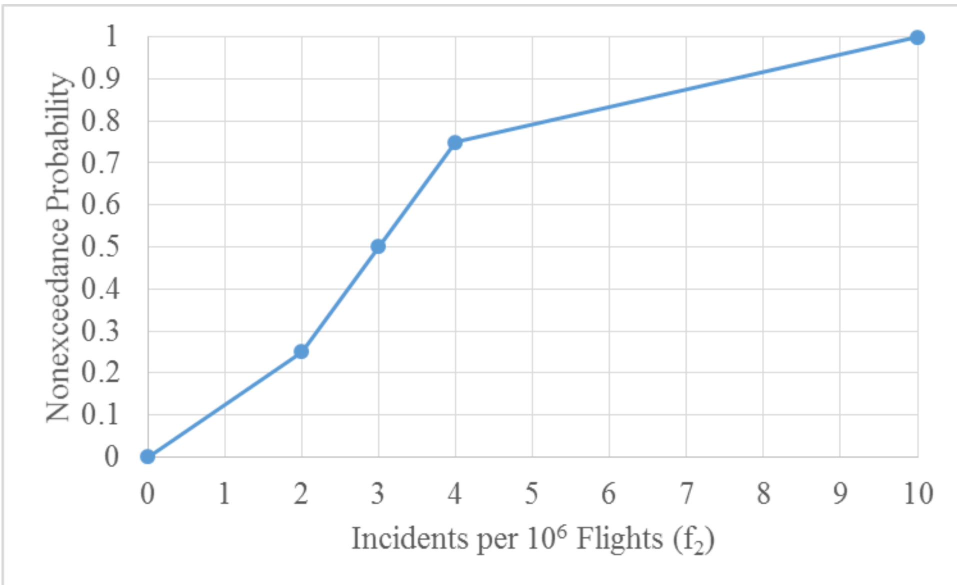

Figure 1. Graphic CDF of incidents per 10^6 flights (fractile method).

From this CDF it is possible to derive a probability denisty function (PDF), where

$$\text{PDF: } p(x) = \frac{dP(x)}{dx}$$

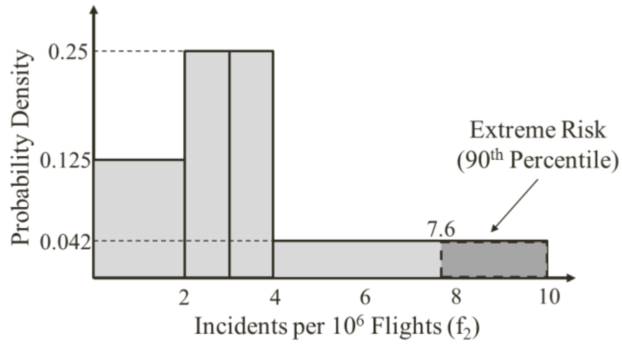

Figure 2. Graphic PDF of incidents per 10^6 flights (fractile method).

The expected value of X, $E[X]$, where p_i is the probability corresponding to x_i incidents per 10^6 flights, and

$$E[X] = \sum_{i=1}^{4} p_i x_i$$

For the example above,

$$E[X] = 0.25\left[0 + \frac{2-0}{2}\right] + 0.25\left[2 + \frac{3-2}{2}\right] + 0.25\left[3 + \frac{4-3}{2}\right] + 0.25\left[4 + \frac{10-4}{2}\right]$$

$$E[X] = 3.5 \text{ incidents per } 10^6 \text{ flights}$$

The triangular distribution is another distribution that is particularly useful when experts cannot identify exact median and quartile points of a CDF. In this method, expert evidence can be solicited to learn only three points: *a* = best case, *b* = worst case, and *c* = most likely. These points are plotted as a PDF that has the shape of a triangle with area = 1. For example consider best case, 0 incidents; worst case, 10 incidents; and most likely, 2 incidents per year. This scenario is represented in triangular PDF form below.

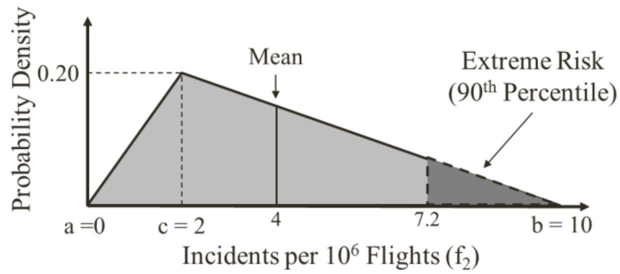

Figure 3. Graphic PDF of incidents per year (tringular distribution).

Knowing only the three points *(a,b,c)*, the expected value and variance of this distribution are computed from the geometry of triangles, and similarly it is possible to find expected values for extreme events (e.g., >90th percentile) [Haimes, 2009].

Mean: $E[X] = \frac{a+b+c}{3}$

Variance: $Var(X) = \frac{a^2+b^2+c^2-ab-ac-bc}{18}$

In the above example, $E[X] = 4$ incidents per 10^6 flights

Using the expert derived objective metrics and distributions, an expected value for incident risk and an expected value for >90th percentile risk (extreme value) will be computed for each scenario. Then for each grouping of scenarios from step 2 (aligned with particular parameters), a plot will be generated with the two objectives as axes, and each scenario will be plotted for two pairs: the efficiency metric, and both the expected value and the extreme value.

2.2.2. Multi-Objective Tradeoff Analysis and Pareto-Optimality.

For the FAA considering UAS integration into the NAS, different policies under consideration can result in various outcomes for improved efficiency and decreased risk (improved safety), the two major objectives of the FAA. As previously discussed, the two objectives are non-commensurate, and this implies there are tradeoffs related through variables such as the distance or time allowed between aircraft, among others. When decisions require tradeoffs between objectives, it is necessary to quantify those tradeoffs in terms of the objective measures relative to each other. When improving one objective can be achieved only at the expense of degrading another, this is termed Pareto-optimality [Haimes 2009]. Pareto-optimality is important when considering new policies because from among all the available policies, only those policies which are Pareto-optimal should be considered; other non-Pareto-optimal solutions would be inferior to, or dominated by, Pareto-optimal ones.

One of the goals of multi-objective tradeoff analysis is to derive explicitly the change to one objective function made by gaining or degrading on the other objectives. When objective functions can be explicitly written in closed-form as functions of the system's state variables, then there are closed-form solutions through calculus using Lagrangian functions and the Kuhn-Tucker optimality conditions [Haimes, 2009]. The solutions to such multi-objective optimization problems define a Pareto-optimal frontier.

However, techniques also exist to construct a Pareto-optimal frontier from a database when closed-form objective functions have not been defined [Haimes, 2009]. Consider a multi-objective problem very similar to the FAA's UAS integration where the objectives are to minimize risk, $min\ f_1(\bullet)$, and minimize airspace inefficiency, $min\ f_2(\bullet)$, and a database of policy scenarios exists that includes the both objective metrics for each scenario, s_i.

Scenario	**$f_1(\bullet)$**	**$f_2(\bullet)$**
s_1	$f_1(s_1)$	$f_2(s_1)$
s_2	$f_1(s_2)$	$f_2(s_2)$
s_3	$f_1(s_3)$	$f_2(s_3)$
s_4	$f_1(s_4)$	$f_2(s_4)$
s_5	$f_1(s_5)$	$f_2(s_5)$
…	…	…
s_n	$f_1(s_n)$	$f_2(s_n)$

Figure 4. A database of objective metrics associated with scenarios.

The points in the database can be plotted on axes of the objective metrics as a scatter plot.

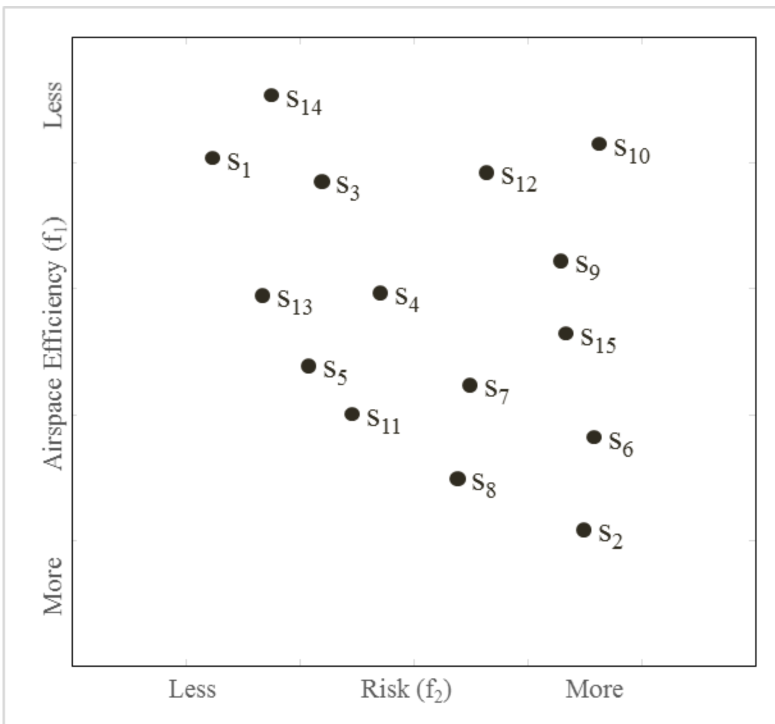

Figure 5. A scatterplot of policy scenarios by objective measures.

Graphical analysis of the above plot above reveals that many of the scenarios are inferior with respect to minimizing both objectives. For example s_{13} has less risk and less inefficiency than s_3; likewise s_8 has less inefficiency than s_7 for approximately the same risk level. However, a subset of the scenarios cannot be said to be inferior to the others in both metrics: s_5 achieves lower risk than s_{11}, but it is also less efficient, and similarly with s_8 and s_2. Applying a similar analysis to all the scenarios, and keeping only those that are not inferior yields the chart below, where all non-inferior points are shown sitting on a fitted line.

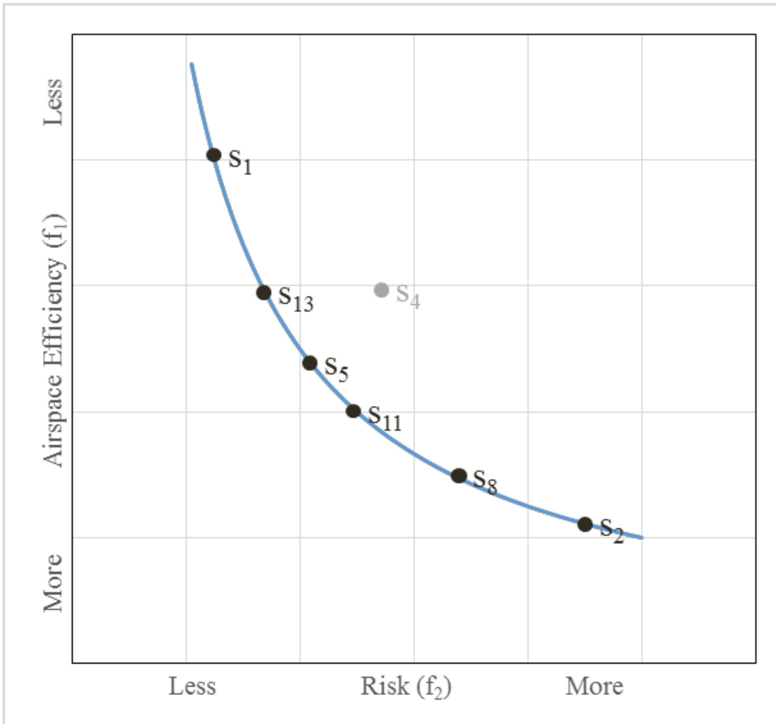

Figure 6. A Pareto-optimal frontier defined by non-inferior scenarios.

That line is the Pareto-optimal frontier for policies in this example. Then the optimal tradeoffs among objectives can be approximated as the slope of the line between two points (as shown between s_1 and s_{13} below).

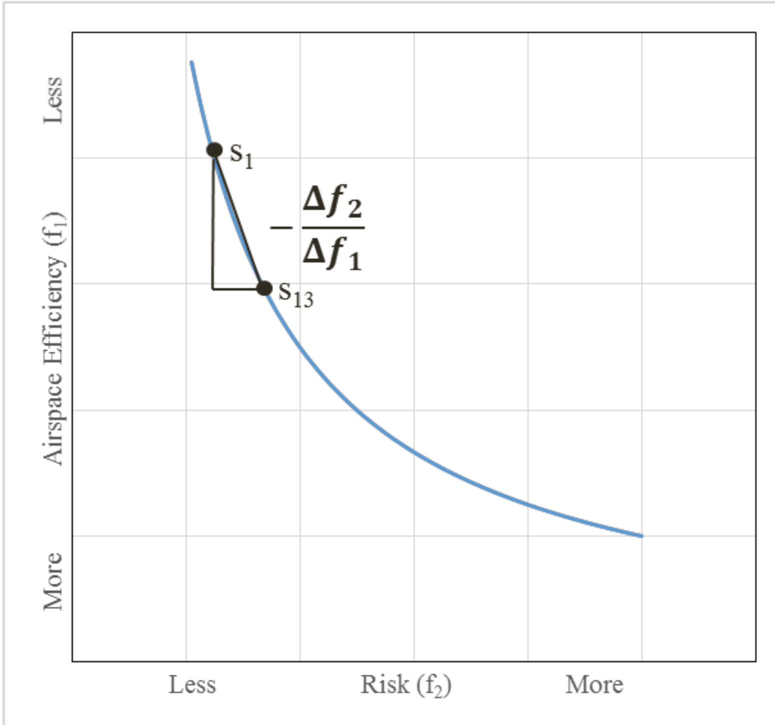

Figure 7. A direct measure tradeoffs between objectives on a Pareto-optimal frontier for two scenarios.

3. National Airspace System Description and Metamodel.

3.1. System Objectives

The FAA's mission is "to provide the safest, most efficient aerospace system in the world" [FAA, Mission]. These two objectives—safety and efficiency—are typically at odds with each other. Efficiency can have several connotations; one aspect of airspace efficiency is how closely the path of aircraft follow the shortest possible path to destination. Inefficiency would manifest in aircraft having to route away from the shortest path in order to avoid other aircraft, etc. Safety is a maximum acceptable level of risk [Haimes, 2009], and in this context the risk stems mostly from a probability of near mid-air collision (NMAC, referred to as an incident hereafter) with other aircraft and the possible consequences of any incident. (For any possible adverse event such as a collision, there will also be a range of possible consequences, each with its own likelihood. This cannot be ignored when considering risk by the classic definition.) The FAA establishes required safety thresholds, but in fact their objective could just as easily be described as minimizing risk, and that will be the connotation that is most helpful in evaluating tradeoffs with other objectives. In much the same way, capacity can be described as the maximum number of aircraft that can occupy a given airspace in a particular scenario. In this connotation, capacity is maximum level of efficiency, which is directly related to the minimum separations (in three or four dimensions) allowed between aircraft under different policies and scenarios.

For the FAA, their two objectives are related primarily through the increased likelihood of incident that occurs with aircraft flying close to each other. That is why airspace management requires establishing separation between aircraft (as in a safety buffer) [FAA, 2008]. However, if the safety buffer is large, and/or the airspace has many aircraft, then some or all aircraft may be forced onto non-optimal paths. Thus minimizing risk (maximizing safety) and maximizing capacity (maximizing efficiency) are competing objectives related through the size and type of separation between aircraft and the other risk management options in use. Types of separation include separation tracked dynamically through 4-D trajectories in TBO [JPDO, 2011] and restricted airspaces such as those currently employed with UAS [FAA, 2013]. Specific risk management policies may also specify the minimum separations, and the required equipment/technologies to be used, among others.

3.2. System Metamodel.

The entire NAS is a complex system of systems, but for the analysis of this specific problem it is more tractable to use a system metamodel representation that can be used to determine metrics for the system's objectives from a limited set of key system state variables. The values of the system state variables are established from parameters that include system input variables, decision variables, and random and exogenous variables. The values of those input parameters are derived from specific scenarios that may occur in the future NAS.

An example of an UAS-NAS integration system model is shown below. In the model input, exogenous, random, and decision variables at certain levels are defined as one specific instantiation of the system, or scenario, which includes the risk management options applied in that case. A particular scenario results in a set of system state variables, $\boldsymbol{s_i}$, that account for the information needed to determine the system's capacity and risk level. In this way, any airspace scenario can either be described in terms of all its input parameters, or more simply in terms of its output. This technique of labeling scenarios according to the state variables and linking them to output will be used later.

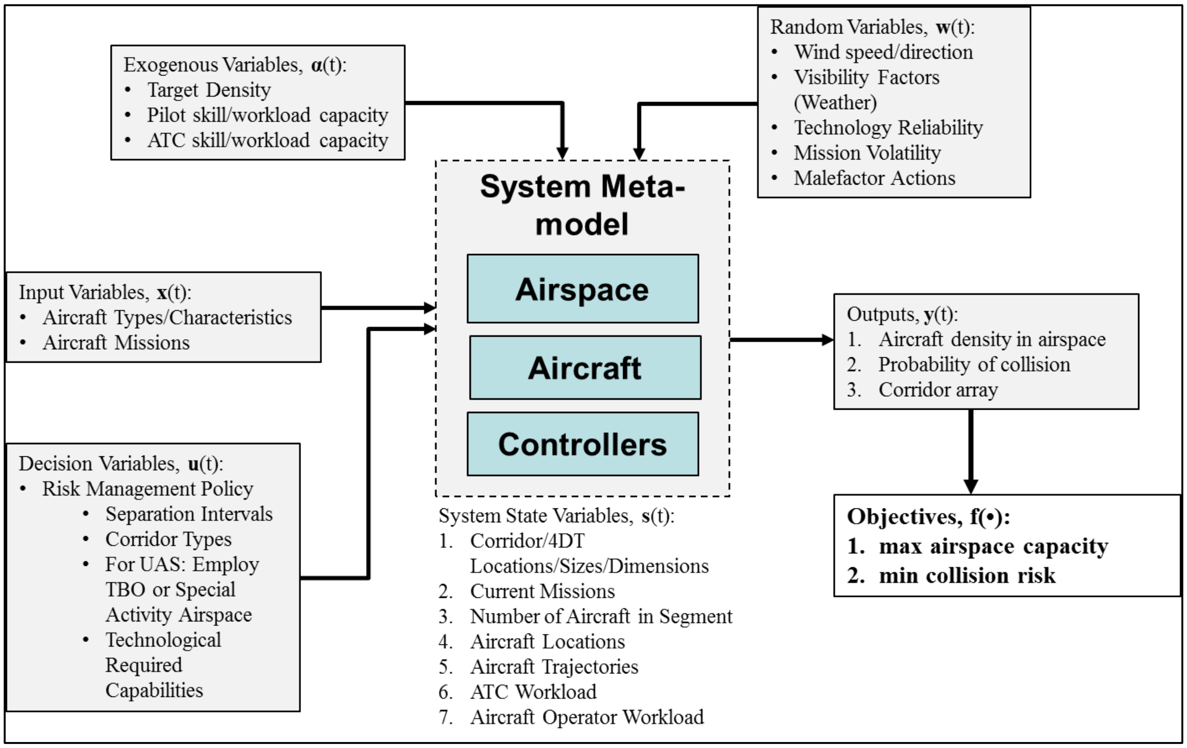

Figure 8. A system metamodel representation for measuring FAA objectives under UAS Integration into the NAS.

4. Methodological Approach to Establishing Tradeoffs among Risk Management Options and System Objectives.

In order to answer specific questions about the tradeoffs between safety and efficiency when UAS are integrated into the NAS, the methodology must translate the qualitative aspects of the system metamodel and likely risk scenarios into a quantitative model. System output data can then be used to quantify the relationship between safety and airspace efficiency under various conditions and policy options. Thus the FAA can clearly understand the tradeoffs in managing risk, and importantly determine whether future decisions about the configuration of the integrated airspace will result in non-inferior tradeoffs.

In this thesis, the scope has been limited to examine two surrogate objectives in a small range of scenarios in order to demonstrate the validity of methodology. In particular, rather than computing the efficiency of the airspace, another metric is being substituted, the airspace capacity. This has been done because of the more straightforward computation of capacity in geometric terms dependent entirely on decision variables for separating aircraft. The relationship between safety and risk has been discussed, and in this method risk is measured as a likelihood of an incident occurring. It is assumed that with more robust resources, the same methodology can be used to measure airspace efficiency, which is dependent on many exogenous and other input variables in addition to decisions about separations. The general approach of the methodology is outlined below.

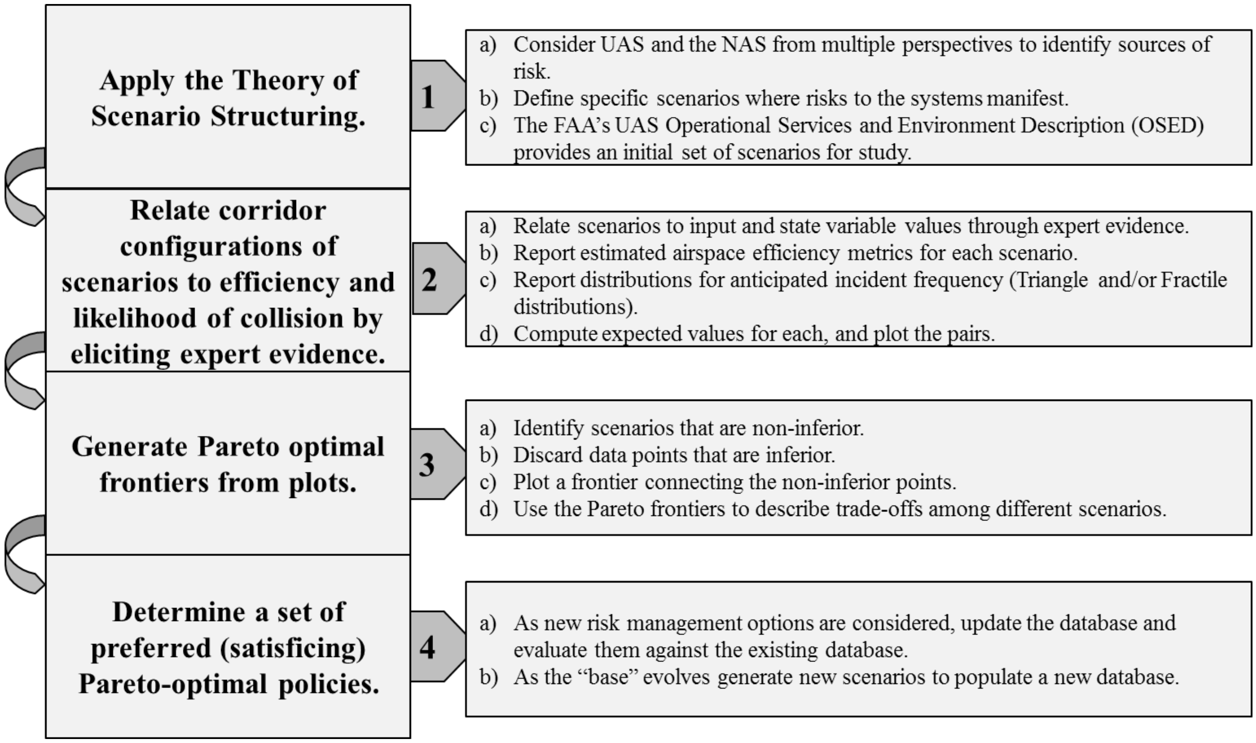

Figure 9. Flowchart for the methodology of this thesis.

4.1 Apply the Theory of Scenario Structuring.

To begin building a database and model of risk and efficiency in airspace, the first step is to generate scenarios. The "theory of scenario structuring" as described by Kaplan et al. [1999] encompasses many concepts about risk that had been explored in earlier works, chiefly that developing risk scenarios (where adverse events and their consequences may manifest) is equivalent to answering the question, "What can go wrong?" Consider UAS and the NAS from multiple perspectives to identify sources of risk. Later Kaplan, Haimes, and Garrick [2001] incorporated into the theory the method of hierarchical holographic modeling (HHM), which is a means of developing a comprehensive scenario set. This thesis used HHM to develop potential risks associated with UAS integration from seven main perspectives, shown in the figure below as the seven head topics. The subtopics under each head topic further differentiate possible sources of risk. In the complete HHM, found in the Appendix 1, particular risk scenarios are matched with each subtopic to identify how they might influence the likelihood or the consequence magnitude of an incident involving a UAS in integrated airspace. In order to scope the project to demonstrate the methodology, only risks associated with the Airspace Structure/Configuration head topic have been considered.

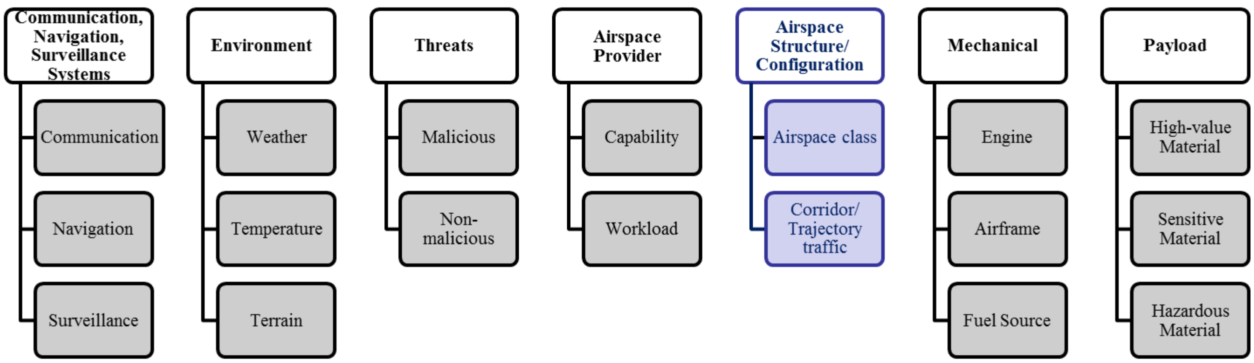

Figure 10. A partial reduced HHM of risk sources across seven perspectives.

Following the comprehensive HHM, it is expected that only a subset of discovered risk scenarios will address the most significant risks to UAS integration. The method of filtering and ranking, also developed by Haimes [2009], is used to reduce the set to a manageable subset that still includes the scenarios that are most likely to occur and/or have the greatest consequences by rating them against Haimes' multiple criteria, also shown in Appendix 1b. In the case of this thesis that procedure was abridged, and for the sake of demonstrating the remainder of the methodology, we concentrate specifically on integration risks associated with the airspace structure and corridor/trajectory configuration in Class A and E airspace in order to demonstrate the methodology.

UAS operating in integrated airspace under a TBO CONOPS represents two new challenges for the FAA, the integration of UAS into airspace shared by manned aircraft (and over populated areas), and the adoption of the TBO CONOPS for all aircraft. In developing a comprehensive scenario set, it is therefore useful to consider scenarios that fall along the dimensions of these broad policy decisions. Within the context of these broad dimensions, there are specific policy variables that determine the spatial separation required between aircraft types. In this way the scenarios can be grouped to compare the tradeoff levels.

In the past, the FAA has relied on standardized scenarios that define the essential flight parameters of a broad range of possible activities and aircraft types. One such document was developed by the Radio Technical Commission for Aeronautics (RTCA) Special Committee 203 (SC203) specifically for the purpose of evaluating aspects of UAS operations in the NAS. That committee's Operational Services and Environment Definition (OSED) [RTCA, 2010] provided a basis for evaluating risk scenarios within an appropriate operational context.

4.2 Relate Corridor Configurations to Efficiency and Risk Metrics.

Estimates from expert evidence can be relied on for populating the database that will be used for modeling tradeoffs for reasons described earlier. The first step in building the database is to identify the system parameter values that relate the scenario to an instance of the system model. For this thesis, the decision variables of interest are the type access granted to UAS, the configuration of the airspace, and the separation requirements between aircraft. Each combination of variables defines a scenario, s_i, and the key output variable information for that scenario is recorded.

For each scenario, we use information about the state of the system to calculate the capacity airspace in that scenario. Capacity is directly computed by dividing a total volume of airspace, by the volume of airspace fixed around an individual aircraft based on separation requirements. This measure of capacity is recorded for each scenario in the database. It should be noted that the separation requirement between aircraft (also called the radius) is the major parameter in computing the capacity for a given volume of airspace.

Following the computation of capacity, we employ one of the two methods of estimating the incident likelihood described before. For this thesis, the Triangle distribution is used, and in place of expert evidence, we made reasonable estimations of the distributions for the various scenarios

4.3. Generate Pareto optimal frontiers from plots.

Following the procedure described earlier, on each scenario-objectives plot, any inferior scenarios will be discarded, and the remaining scenarios will define a Pareto-optimal frontier. The frontier will be used to describe the objective tradeoffs between Pareto-optimal scenarios.

4.4. Determine a Set of Preferred Pareto-Optimal Policies for Multiple Objectives.

By defining the tradeoff curves between two objectives, different overall CONOPS can be compared directly. Here, the CONOPS being compared are derived from combinations of major decision variables, u_i: the type of access granted to the UAS (u_1), and the configuration of the airspace (u_2), and the minimum separation requirements (u_3). We consider two types of access for decision variable u_1: integration where UAS are not differentiated from manned aircraft or integration where UAS maintain different separation standards than manned aircraft. Likewise the configuration of the airspace is considered at two levels for decision variable u_2: a configuration of multiple parallel sub-corridors in a single corridor (for each flight's trajectory) or a mixed configuration of crossing trajectories. The decision variable u_3 for separation minimums could be considered as a continuous variable, but in practice only discrete values are input to create scenarios. However, when scenarios are grouped by like decision values for u_1 and u_2, the varying levels of the u_3 variable (minimum separation) lead to the output variable pairs for the capacity and risk objectives, which subsequently we plot to form Pareto-optimal frontiers.

	Parallel Trajectories (u_2=1)	Crossing Trajectories (u_2=2)
UAS Fully Integrated – Undifferentiated (u_1=1)	(u_1=1,u_2=1,u_3)	(u_1=1,u_2=2,u_3)
UAS Integrated – Differentiated (u_1=2)	(u_1=2,u_2=1,u_3)	(u_1=2,u_2=2,u_3)

(u_1=1,u_2=1,u_3)

Scenario	Minimum Separation u_{3j}	Efficiency Metric $f_1(\bullet)$	Risk Metric $f_2(\bullet)$
s_1	u_{31}	$f_1(s_1)$	$f_2(s_1)$
s_2	u_{32}	$f_1(s_2)$	$f_2(s_2)$
s_3	u_{33}	$f_1(s_3)$	$f_2(s_3)$
s_4	u_{34}	$f_1(s_4)$	$f_2(s_4)$
s_5	u_{35}	$f_1(s_5)$	$f_2(s_5)$
...	...	...	...
s_n	u_{3n}	$f_1(s_n)$	$f_2(s_n)$

(u_1=1,u_2=2,u_3)

Scenario	Minimum Separation u_{3j}	Efficiency Metric $f_1(\bullet)$	Risk Metric $f_2(\bullet)$
s_1	u_{31}	$f_1(s_1)$	$f_2(s_1)$
s_2	u_{32}	$f_1(s_2)$	$f_2(s_2)$
s_3	u_{33}	$f_1(s_3)$	$f_2(s_3)$
s_4	u_{34}	$f_1(s_4)$	$f_2(s_4)$
s_5	u_{35}	$f_1(s_5)$	$f_2(s_5)$
...	...	...	...
s_n	u_{3n}	$f_1(s_n)$	$f_2(s_n)$

(u_1=2,u_2=1,u_3)

Scenario	Minimum Separation u_{3j}	Efficiency Metric $f_1(\bullet)$	Risk Metric $f_2(\bullet)$
s_1	u_{31}	$f_1(s_1)$	$f_2(s_1)$
s_2	u_{32}	$f_1(s_2)$	$f_2(s_2)$
s_3	u_{33}	$f_1(s_3)$	$f_2(s_3)$
s_4	u_{34}	$f_1(s_4)$	$f_2(s_4)$
s_5	u_{35}	$f_1(s_5)$	$f_2(s_5)$
...	...	...	...
s_n	u_{3n}	$f_1(s_n)$	$f_2(s_n)$

(u_1=2,u_2=2,u_3)

Scenario	Minimum Separation u_{3j}	Efficiency Metric $f_1(\bullet)$	Risk Metric $f_2(\bullet)$
s_1	u_{31}	$f_1(s_1)$	$f_2(s_1)$
s_2	u_{32}	$f_1(s_2)$	$f_2(s_2)$
s_3	u_{33}	$f_1(s_3)$	$f_2(s_3)$
s_4	u_{34}	$f_1(s_4)$	$f_2(s_4)$
s_5	u_{35}	$f_1(s_5)$	$f_2(s_5)$
...	...	...	...
s_n	u_{3n}	$f_1(s_n)$	$f_2(s_n)$

Figure 11. A partition of scenarios on two decision variables for risk management options. Each set of partitioned scenarios leads to a particular Pareto-optimal tradeoff curve for that combination of risk management options.

Thus, each pair of decision variables (u_1, u_2), for access type and airspace configuration, along with a choice of minimum separation becomes a distinct risk management option for controlling the risk of an incident. Pareto-optimal frontier curve for a risk management option. By overlaying these separate curves on each other, we then generate a global Pareto-optimal frontier that represents the best available tradeoffs. As new or different risk management policies are examined in the future (due to the evolving base), those options may be compared against the existing system in the same way. Similarly, existing and proposed airspace rules may be reevaluated with updated objective metrics to account for refinements in models or the expansion of the database with real-world events and scenarios as UAS integration into the NAS proceeds.

5. Demonstration of Method and Analysis.

5.1. Key Assumptions.

Several simplifying assumptions are made in order to demonstrate the techniques proposed above:

1. Capacity is a surrogate metric for efficiency. The actual realized efficiency is affected by many other factors, including the amount of air traffic control and the number of aircraft that are actually flying. Regardless the capacity of the airspace is an upper bound of achievable efficiency measured as the density of aircraft in an airspace.
2. The airspace is limited to a single flight level. This simplifies the airspace to a two dimensional space for analysis.
3. Aircraft have similar capabilities and fly at the same speeds in a given airspace. This assumption allows aircraft to be considered stationary relative to each other if they are on parallel trajectories.
4. All scenarios use a uniform 100 nautical mile (nm) by 100 nm airspace (10,000 nm^2). Separation requirements are also given in nm.
5. The proportion aircraft in the integrated airspace that are UAS is 10%.
6. When computing capacities, numbers are rounded down to the nearest integer.
7. Capacity is computed the same for both parallel and crossing trajectory airspaces; based on that, crossing trajectories are riskier.
8. The majority of random, exogenous, and other input variables are not explicitly considered, but are considered uniform across scenarios.
9. Within considered risk management policies, only the required separation between aircraft determines the airspace capacity. Therefore minimizing the required separation is equivalent to maximizing capacity.
10. The estimated incident rate does not correspond to an airspace that is operating at full capacity; it is assumed that only a fraction of actual capacity is used during normal flight operations.
11. The data presented in the following sections is assumed to be of similar order of magnitude to expected real world results, but it is not drawn from any actual database or evidence elicited from experts, and should not be considered authoritative. It is for demonstrative purposes only.

All of these assumptions are made without loss of applicability of the method of comparing multiple objectives. Considering additional variables and scenarios modeled increases the complexity of computing objective metrics without affecting the ability to establish a global Pareto-optimal frontier or evaluate tradeoffs between objectives on it.

5.2. Risk Management Policies Considered.

As described in the preceding section, three decision variables are considered for each scenario in this demonstration analysis. The two true FAA objectives are maximize safety and maximize efficiency, but for this analysis the following objectives are considered acceptable surrogates:

1. Maximize the airspace capacity, $f_1(\bullet)$. (Or alternately, minimize the required separation between aircraft $f_1{}'(\bullet)$, as explained below.)
2. Minimize the frequency of incidents, $f_2(\bullet)$.

These objectives are functions of three decision variables which constitute a risk management policy. The decision variables are:

$$u_1 = extra\ factor\ imposed\ on\ UAS\ minimum\ separation\ standards$$

$$u_2 = configuration\ of\ the\ airspace$$

$$u_3 = the\ minimum\ separation\ requirement\ between\ manned\ aircraft$$

The table below shows the possible ranges for the decision variables considered and the meaning.

Variable	**Level 1**	**Level 2**
u1	1 (no difference in standards)	2 (UAS required to maintain twice the manned separation)
u2	1 (parallel trajectories)	2 (crossing trajectories)
u3	Sampled from range [0.25nm, 7nm]	

Figure 12. Ranges for decision variables.

Broadly, the risk management policies are defined by the combination of the variables u_1 and u_2, while the value of u_3 is a particular risk management option within a policy. Each scenario is based on a specific combination of the three decision variables: $u_1(s_i), u_2(s_i), u_3(s_i)$.

It follows that each scenario achieves objective measures as functions of the decision variables:

$\boldsymbol{f_1}\big(u_1(s_i), u_2(s_i), u_3(s_i)\big)$, the capacity metric
$\boldsymbol{f_2}\big(u_1(s_i), u_2(s_i), u_3(s_i)\big)$, the risk metric

When considering the combinations of variables to create risk management policies, there are four possibilities to create different Pareto-optimal curves to compare against one another:

$\boldsymbol{f_1}\big(1,1, u_3(s_i)\big)$ $\boldsymbol{f_2}\big(1,1, u_3(s_i)\big)$	$\boldsymbol{f_1}\big(1,2, u_3(s_i)\big)$ $\boldsymbol{f_2}\big(1,2, u_3(s_i)\big)$
$\boldsymbol{f_1}\big(2,1, u_3(s_i)\big)$ $\boldsymbol{f_2}\big(2,1, u_3(s_i)\big)$	$\boldsymbol{f_1}\big(2,2, u_3(s_i)\big)$ $\boldsymbol{f_2}\big(2,2, u_3(s_i)\big)$

Figure 13. Objective pairs that establish tradeoff curves for the four broad risk management policies.

5.3. Computation of Capacity.

We compute the capacity of the airspace as the maximum number of aircraft that can occupy a given area of airspace at a time according to required separation standards in effect for each scenario. This computation is based on the following factors:

A_T: *total area of airspace*

m: *factor by which UAS separations are larger than manned aircraft*

n: *number of manned aircraft per UAS in the airspace*

r_m: *separation standard for manned aircraft*

$A_m = r_m^2$: *area occupied by single manned aircraft (safety buffer)*

$A_U = m^2 r^2$: *area occupied by single UAS (safety buffer)*

From these factors it is possible to compute the number of manned aircraft (x_m) and the number of UAS (x_U), and the total airspace capacity ($x_m + x_U$) using the following approach:

$$A_T = A_m x_m + A_U x_U$$

$$A_T = r_m^2 x_m + m^2 r_m^2 x_U$$

$$A_T = r_m^2 x_m + m^2 r_m^2 \left(\frac{x_m}{n}\right)$$

$$A_T = \left(1 + \frac{m^2}{n}\right) r_m^2 x_m$$

$$x_m = \frac{A_T}{\left(1 + \frac{m^2}{n}\right) r_m^2}$$

$$x_U = \frac{x_m}{n}$$

$$Capacity = x_m + x_U$$

(When the factors f and n are held constant, the airspace capacity is proportional to $\left(\frac{1}{r_U^2}\right)$. In most of the graphs that follow in the analysis section, minimizing r_U is depicted as a surrogate objective for maximizing capacity in order to clarify interpretation of the graphs.)

5.4. Scenarios Considered and Estimates of Objective Function Values.

A total of 40 scenarios are evaluated, in collections of 10 that correspond with the broad risk management policy, as shown in the tables below. In each collection, the first column is the scenario number, the second column is the value of the third decision variable u_3, and the third column is the effect of the decision variable u_1. The Incident Distribution is the estimate of the distribution of incidents per million flight operations using a triangle distribution (which is to be determined through expert evidence in practice). The final two columns are the computed objective function values for capacity and expected incident rate based on the separations and distributions. (Note that the third column is also the value of f_1 ' (•), which will be used for graphic analysis.)

Scenario	$u_3 = r_m$ (Minimum Separation for Manned Aircraft in nm)	$r_U = f_1'(\bullet)$ Minimum Separation - UAS (nm)	Incident Distribution	Obj. $f_1(\bullet)$ Airspace Capacity (AC per 100nm x 100nm)	Obj. $f_2(\bullet)$ E[Incidents]
s_1	0.25	0.25	Tri(3,50,1000)	160000	351.0
s_2	0.5	0.5	Tri(2,25,700)	40000	242.3
s_3	0.75	0.75	Tri(0,15,400)	17777	138.3
s_4	1	1	Tri(0,10,250)	10000	86.7
s_5	2	2	Tri(0,6,100)	2500	35.3
s_6	3	3	Tri(0,4,34)	1111	12.7
s_7	4	4	Tri(0,3,15)	624	6.0
s_8	5	5	Tri(0,2,6)	400	2.7
s_9	6	6	Tri(0,1,3)	277	1.3
s_{10}	7	7	Tri(0,0,2)	203	0.7

Figure 14. The policy collection representing no additional separation requirements for UAS and parallel trajectories. $(u_1(s_i) = 1, u_2(s_i) = 1, u_3(s_i))$.

Scenario	$u_3 = r_m$ (Minimum Separation for Manned Aircraft in nm)	$r_U = f_1'(\bullet)$ Minimum Separation - UAS (nm)	Incident Distribution	Obj. $f_1(\bullet)$ Airspace Capacity (AC per 100nm x 100nm)	Obj. $f_2(\bullet)$ E[Incidents]
s_{11}	0.25	0.5	Tri(2,30,800)	123076	277.3
s_{12}	0.5	1	Tri(1,12,600)	30768	204.3
s_{13}	0.75	1.5	Tri(0,10,300)	13674	103.3
s_{14}	1	2	Tri(0,3,200)	7692	67.7
s_{15}	2	4	Tri(0,0,80)	1922	26.7
s_{16}	3	6	Tri(0,0,30)	854	10.0
s_{17}	4	8	Tri(0,0,15)	480	5.0
s_{18}	5	10	Tri(0,0,5)	306	1.7
s_{19}	6	12	Tri(0,0,3)	213	1.0
s_{20}	7	14	Tri(0,0,2)	156	0.7

Figure 15. The policy collection representing double separation requirements for UAS and parallel trajectories. $(u_1(s_i) = 2, u_2(s_i) = 1, u_3(s_i))$.

Scenario	$u_3 = r_m$ (Minimum Separation for Manned Aircraft in nm)	$r_U = f_1'(\bullet)$ Minimum Separation - UAS (nm)	Incident Distribution	Obj. $f_1(\bullet)$ Airspace Capacity (AC per 100nm x 100nm)	Obj. $f_2(\bullet)$ E[Incidents]
s_{21}	0.25	0.25	Tri(20,50,1200)	160000	423.3
s_{22}	0.5	0.5	Tri(12,35,840)	40000	295.7
s_{23}	0.75	0.75	Tri(10,25,480)	17777	171.7
s_{24}	1	1	Tri(5,15,300)	10000	106.7
s_{25}	2	2	Tri(3,9,120)	2500	44.0
s_{26}	3	3	Tri(1,3,70)	1111	24.7
s_{27}	4	4	Tri(0,1,20)	624	7.0
s_{28}	5	5	Tri(0,0,7)	400	2.3
s_{29}	6	6	Tri(0,0,4)	277	1.3
s_{30}	7	7	Tri(0,0,3)	203	1.0

Figure 16. The policy collection representing no additional separation requirements for UAS and crossing trajectories. $(u_1(s_i) = 1, u_2(s_i) = 2, u_3(s_i))$.

Scenario	$u_3 = r_m$ (Minimum Separation for Manned Aircraft in nm)	$r_U = f_1'(\bullet)$ Minimum Separation - UAS (nm)	Incident Distribution	Obj. $f_1(\bullet)$ Airspace Capacity (AC per 100nm x 100nm)	Obj. $f_2(\bullet)$ E[Incidents]
s_{31}	0.25	0.5	Tri(14,35,1100)	123076	383.0
s_{32}	0.5	1	Tri(8,20,750)	30768	259.3
s_{33}	0.75	1.5	Tri(7,17.5,430)	13674	151.5
s_{34}	1	2	Tri(3,7.5,250)	7692	86.8
s_{35}	2	4	Tri(2,5,110)	1922	39.0
s_{36}	3	6	Tri(0,0,60)	854	20.0
s_{37}	4	8	Tri(0,0,15)	480	5.0
s_{38}	5	10	Tri(0,0,6)	306	2.0
s_{39}	6	12	Tri(0,0,3)	213	1.0
s_{40}	7	14	Tri(0,0,2)	156	0.7

Figure 17. The policy collection representing double separation requirements for UAS and crossing trajectories. $(u_1(s_i) = 1, u_2(s_i) = 2, u_3(s_i))$.

5.5. Graphic Analysis of Pareto-Optimality

Once a database of scenarios is established, and the key variables are used to estimate the objective function values, those data pairs for each scenario are plotted in order to determine the Pareto-optimal risk management options. For convenience we continue to group them by risk management policy collection, though this is not required. From the graph below it is not immediately obvious which scenarios define the Pareto-optimal frontier, or if they come from different risk management policies.

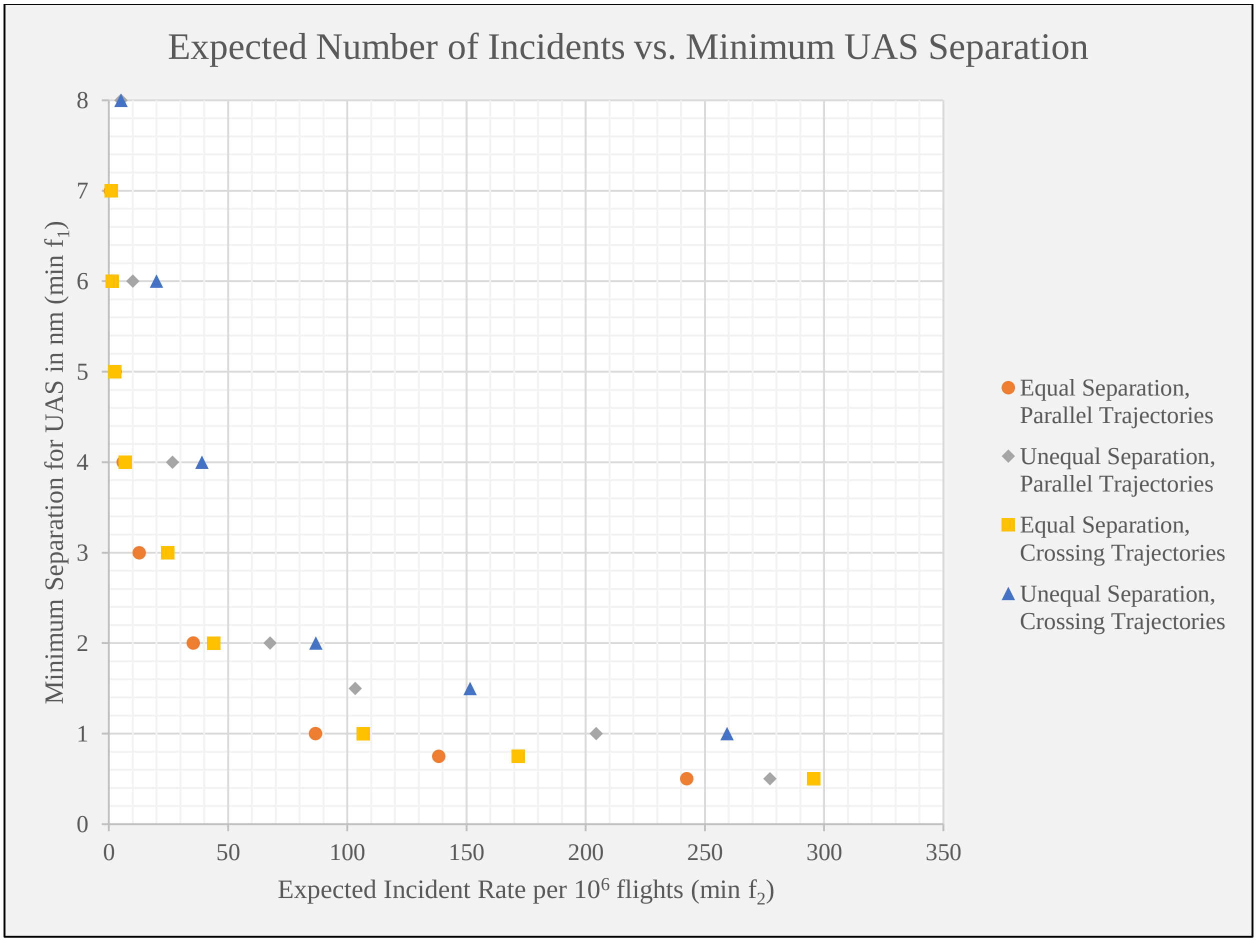

Figure 18. A combined plot of the objective pairs for all 40 scenarios. Many non-optimal scenarios are apparent, but discerning the Pareto-optimal frontier is not clear.

For this reason we add lines to connect the data pairs from like collections, as seen on the next graph. Now it is clear that the scenarios associated with decision variables equal separations and parallel trajectories form a Pareto-optimal curve, and that the collection of scenarios for that risk management policy dominate the other alternatives.

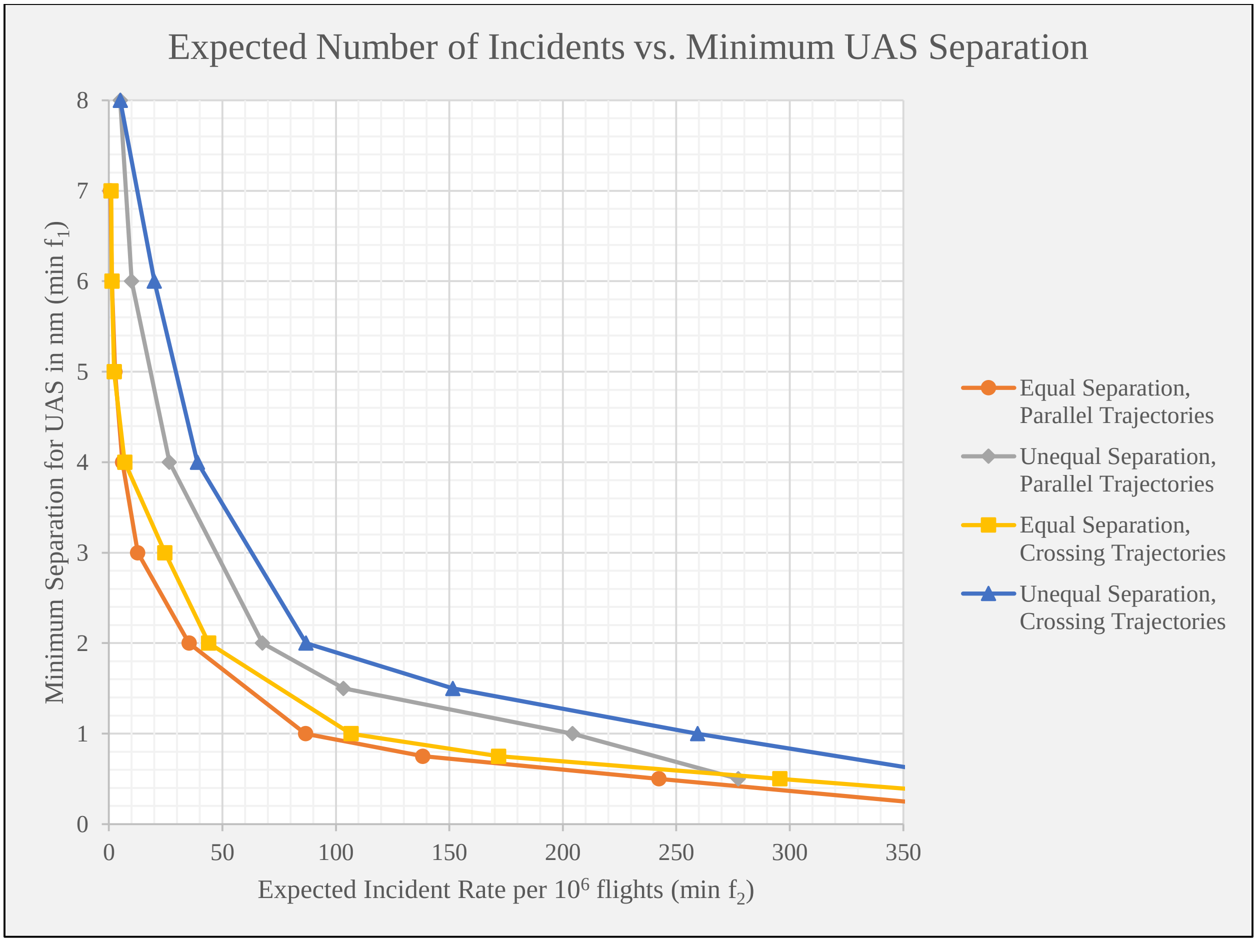

Figure 19. An overlay graph showing clearly that for the given database, the risk management policy of allowing equal separation, but requiring parallel trajectories is optimal for all objective levels.

Based on this analysis, a preferred CONOPS for UAS integration would route UAS along trajectories parallel to other air traffic, but allow them to operate with the same separation standards as manned aircraft. This would seem to restrict the application of Trajectory-Based Operations in the CONOPS. However, this is based on an assumption of a single flight level (two-dimensional airspace). The introduction of additional flight levels for trajectory planning (changing the assumptions and/or expanding the model variables under consideration) may result in a different analysis that favors TBO.

There is also a possibility that two or more different risk management policies together form an optimal “envelope” (Haimes and Anderegg, 2013] at different points along the curve. In this case FAA policy makers may choose to implement multiple policies but apply them conditionally only in particular scenarios when they are best.

6. Directions for Future Work

There will be many sources of uncertainty as the NextGen NAS develops over time. One of the major uncertain variables will be the proliferation and expansion of the numbers of UAS relative to the numbers of manned aircraft operating in the NAS. For the preceding analysis, we assume 10% of aircraft are unmanned, but another assumption might be that the numbers of UAS will grow over time. The principles contained in this thesis also apply to projecting policy decisions into the future.

Consider that based on the analysis above, the FAA two policies are optimal at different points along an envelope. If it is assumed that implementing both is not feasible, and choosing one or the other implies some commitment of resources for training, programming, etc., then it is prudent to evaluate the impact of the decision on future options. A greater proportion of UAS in the future may result in different objective measures and different tradeoff curves depending on the policy chosen now.

Haimes and Anderegg [2013] provide a framework for performing multi-period Pareto-optimal risk analysis using the envelope approach. That method is currently very well suited to assessing future risks of current decisions based on a known series of decisions in successive periods where the decision space for each decision is somewhat known; it also works very well when cost is explicitly or implicitly one of the system objectives. Haimes and Anderegg have also demonstrated the principles qualitatively for a problem related to UAS integration into the NAS However, an adaptation of the envelope approach could also show promise in evaluating uncertainty where the decision space is not known in advance, and be quantified to complement analysis such as described in this thesis.

7. Contribution of Thesis.

All decisions are made to maintain or alter the states of the system under consideration in order to achieve specific objectives at acceptable tradeoffs [Haimes, 2009]. It is in this context that we develop in this thesis a quantitative approach for the comparison of such tradeoffs associated with airspace efficiency and risk of incident for an UAS-integrated NAS. We believe this is a novel approach in this discipline in that it avoids the pitfalls from a public policy perspective that are often associated with implying a sacrifice to safety in order to improve another objective metric. Rather, this approach results in risk management options being compared against each other to determine when and how a particular policy is superior to another for all objectives, and along the entire Pareto-optimal frontier.

By the method described, we quantify the tradeoffs between two conflicting and competing objectives: i) maximizing efficient use of airspace capacity, and ii) minimize the risk of collision among one or more aircraft. In addition to generating Pareto-optimal frontiers associated with different policy/risk management options; we also are able to derive the tradeoffs associated to each policy between capacity and risk of incident. This approach enables us to explore multiple options in the use of airspace, the associated risk for each one, and ultimately develop an effective risk management process by which to derive effective policy not only for the present, but also their propagation and impact on future options.

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Appendix 1. Holographic Hierarchical Model of Sources of Risk

Sources of Risk for Integration of UAS into National Airspace System
1) Communication, Navigation, Surveillance Systems
a) Communication
i) UAS Pilot to Manned Pilot – UAS Pilot does not have direct comm link to other pilots in airspace
ii) UAS Pilot to Controller – UAS pilot loses direct comm link to ATC or service provider
iii) Controller to Manned Pilot – ATC unable to contact manned pilot
iv) UAS Pilot to UAS Pilot – two UAS pilots operating from remote locations in the same airspace do not have direct communications
v) Latency
(1) voice traffic volume leads to delays in voice instructions from controllers to pilots
(2) data traffic volumes causes critical information to be dropped or missed
b) Navigation
i) GPS – a problem with the GPS receiver of the UAS resulting in inaccurate position or large CEP
ii) Data link to Airspace Provider – a problem (latency or lost link) with the connection to the service provider that reports position to the broader system
c) Surveillance
i) ADS-B
(1) "In"- equipped – UAS Pilot in control station sees discrepancy between ADS-B In data and external data
(2) "Out"-equipped – UAS is only ADS-B Out equipped, pilot relies on external data for SA, latency issues
(3) Latency – frequency of updates to the system less than the closing speed of nearby aircraft
(4) Accuracy – related to navigation system
ii) Sense and Avoid System
(1) Coverage – The sensing system in the UAS has a limited coverage area forward of the aircraft
(2) Range – The sensors have a limited range
(3) Quality – the sensors have limited resolution/ability to discern potential threats, ability varies according to environment
iii) Collision Avoidance System
(1) Algorithms
(a) In UAS on UAS collision, the evasive actions aren't coordinated using a known standard

(b) In manned on UAS collision, the manned aircraft pilot does not know what action the UAS is programmed to take
2) Environment
a) Weather
i) Clouds – clouds or fog limits the range and effectiveness of some sensors in UAS SAA systems
ii) Thunderstorms – manned aircraft usually adjust course to avoid passing through known storms which may cause route conflicts and congestion of airspace on bypass routes
iii) High Winds – high winds may affect navigation performance of small UAS, and force them off of preplanned routes
iv) Turbulence
(1) manned aircraft avoid turbulent areas forcing onto congested alternate routes
(2) strong turbulence may damage UAS control surfaces or CNS equipment
b) Temperature
i) Extreme cold
(1) Causes SAA sensors to be less effective
(2) Ice causes loss of control surface
ii) Extreme heat
(1) Negative effects on electrical/mechanical performance
(2) Communications and electronics at risk of malfunction
c) Terrain
i) Mountains/hills – UAS at greater risk of CFIT depending on SAA systems capability
ii) Structures
(1) Buildings - CFIT
(2) Towers - CFIT
(3) Temporary Structures – cranes and other temporary structures may not
3) Threats
a) Malicious
i) Terrorist/Enemy
(1) Cyber-hijack
(a) UAS-as-missile – UAS could be hijacked to deliberately collide with other aircraft or infrastructure
(b) Payload theft – UAS could be stolen
(c) Weapons smuggling – UAS used to smuggle WMD
(2) NAS Disruption – UAS could be flown through congested airspace to cause system disruptions
(3) Unauthorized entry to NAS from outside

(a) Authentication – Airspace service provider cannot verify identity of UAS
(b) Identification - An unauthorised UAS does not provide identification on entry
(i) Malicious UAS pilot does not check in with airspace service provider or provides false ID
(ii) Malicious UAS not equipped with location reporting equipment, only detectable by radar
ii) Criminal
(1) Payload theft – same as terrorist
(2) Mischief – same as terrorist
(3) Smuggling – Smugglers attempt to bring illicit drugs across the borders using UAS and do not report activity to FAA or other craft.
b) Non-malicious
i) Unauthorized Airspace User
(1) Off-course – an airspace user deviates the designated flight plan into the trajectory of the UAS
(2) Off-altitude – an airspace user is operating unknowingly at the same flight level as a UAS
ii) Disruption of Critical Infrastructure
(1) Power grid – a power outage affects the UAS ground control station
(2) GPS – a disruption of GPS service leaves the UAS without navigation capability
(3) Control Stations – any other natural disaster or accidental damage occurs to the control station that disrupts the communication and data links between the pilot, the UAS, or the ATC
iii) General Aviation – GA aircraft with minimum equipment (ADS-B, etc.) fly unpredictable routes in uncontrolled airspace.
iv) Hobbyists – "big sky little bullet"
(1) Balloons – can operate at high altitude, may be difficult to detect with SAA
(2) Rockets – rapid closing speed, difficult to detect with SAA
(3) Model Aircraft – small size makes detection difficult
4) Airspace Provider
a) Capability
i) Data – data channels have maximum bandwidth
ii) Voice – voice communications subject to delay and error
iii) Radar
(1) radar as a backup to GPS becomes secondary, less attention paid
(2) radar less effective at detecting small UAS
b) Workload
i) Human

(1) Controllers and supervisors subject to fatigue/inattention
(2) Controllers at maximum capacity more prone to errors
ii) Machine/Computer
(1) Automation systems not properly backed-up
(2) Automation systems not able to exceed maximum capacities for even short periods
5) Airspace Structure/Configuration
a) Airspace class
i) A, E, Ocean
(1) UAS shares airspace with high-performance aircraft with limited maneuverability to speed ratio
(2) Manned aircraft operating in A, Oceanic typically on autopilot, less attention from pilots to environment
ii) B, C, D – UAS route conflicts with approach or departure routes for airport
iii) G – UAS shares airspace with aircraft not under ATC control, no coordinated flight management
b) Corridor traffic
i) Passenger service – UAS sharing airspace with passenger services results in greater consequence of collision
ii) High-Traffic Corridors – UAS operates in close proximity to other aircraft
iii) Low-Traffic Areas – pilots become complacent due to lack of perceived risk
6) Mechanical
a) Engine
i) Failure – UAS engine fails causing rapid loss of altitude and control of trajectory, no redundant engine
ii) Underperformance – UAS must alter flight path unexpectedly to maintain altitude
b) Airframe
i) Failure – the UAS comes apart in the air
ii) Loss of control surface – the UAS has limited controllability due to damage to a rudder or elevator
c) Fuel Source
i) Duration – weather effects cause the UAS to have a drastically shortened range
ii) Hazardous Material – the fuel source of the UAS contains hazardous materials
7) Payload
a) High-value Material -
b) Sensitive Material – a collision involving a UAS result in theft of classified or sensitive materials to criminal or enemy
c) Hazardous Material – a collision involving a UAS releases hazardous material

Appendix 2. Multi-Criteria Evaluation of Risks from Airspace Structure/Configuration.

HHM: Sources of Risk for Integration of UAS into National Airspace System	Risk Evaluation Criteria										
	1. Undetectability	2. Uncontrollability	3. Multiple Paths to Failure	4. Irreversibility	5. Duration of Effect	6. Cascading Effects	7. Operating Environment	8. Wear and Tear	9. Hardware/ Software/ Human/Org	10. Complexity/ Emergent Behaviors	11. Design Immaturity
5) Airspace Structure/Configuration											
a) Airspace class											
i) A, E, Ocean											
(1) UAS shares airspace with high-performance aircraft with limited maneuverability to speed ratio	Low	Low	Medium	High	High	Medium	High	Low	High	Low	High
(2) Manned aircraft operating in A, Oceanic typically on autopilot, less attention from pilots to environment	Low	Low	Medium	High	High	Low	High	Low	High	Low	Low
ii) B, C, D – UAS route conflicts with approach or departure routes for airport	Low	Low	High	High	High	High	High	Low	High	Medium	Medium
iii) G – UAS shares airspace with aircraft not under ATC control, no coordinated flight management	Medium	Low	Medium	High	High	Low	Medium	Low	Medium	Low	Low
b) Corridor traffic											
i) Passenger service – UAS sharing airspace with passenger services results in greater consequence of collision	Low	Low	Low	High	High	Low	High	Low	High	Low	High
ii) High-Traffic Corridors – UAS operates in close proximity to other aircraft	Low	Low	Low	High	High	Medium	High	Low	High	Low	High
iii) Low-Traffic Areas – pilots become complacent due to lack of perceived risk	Medium	Low	Low	Low	High	Low	High	Low	Low	Low	Low