

Analytical and Empirical Analysis of the Impacts of Restricting Airspace

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Abstract

An analytical model is presented to enable rapid estimation of the impact of airspace restrictions on air traffic. The model outputs the number of aircraft – airspace conflicts as a function of airspace volume, active duration, mean traffic density, and mean transit time across the airspace. An empirical validation of the model using the MITRE Collaborative Routing and Coordination Tools was performed, showing a highly-correlated fit of conflict counts to the analytical model. Simulation data are also provided illustrating the number of induced secondary conflicts due to rerouting traffic as a function of traffic density and restricted airspace size. Additionally, the transient effects of conflicts when airspace is activated or deactivated are described.

Introduction

Large volumes of airspace are routinely restricted from conventional air traffic to prevent overflight of sensitive areas or enable special operations ranging from military training to space launch and recovery. This facilitates air traffic management by reducing the number of factors that controllers must take into account while directing operations in a given region. Flight plans can be compared against the active Special Use Airspace (SUA) and modified if necessary to prevent entry. Aircraft currently in flight are also monitored to ensure that they comply with their flight plans and do not stray into SUA.

As one example, the SUA associated with the US Eastern Launch Range in Florida is depicted in Figure 1. This SUA becomes active – effectively restricted to all external air traffic – for a period from about three hours before a launch or re-entry until shortly after the operation has been completed. This establishes a large temporal and spatial safety buffer between the space operations (and related auxiliary

operations such as weather soundings or chase aircraft) and air traffic. Unfortunately, it also contributes to congestion and delays, as all flights that would normally have passed through that airspace (over 30,000 nmi² in area) must be diverted around it.

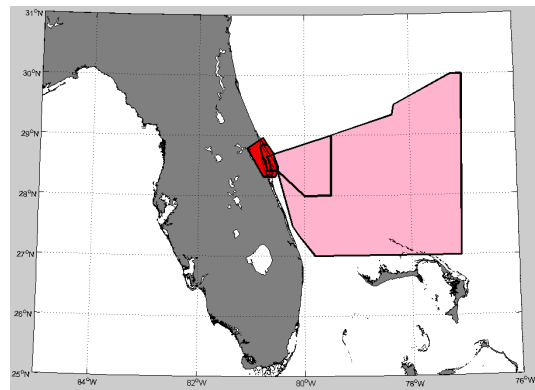


Figure 1: Special Use Airspace (SUA) Associated with the US Eastern Launch Range

This problem is not limited to space launch, nor to the US. Restricting airspace for other purposes, such as military operations, imposes similar impacts on air traffic worldwide. More than 1,000,000 square miles of US airspace is designated for military operations, though most of this is activated only as needed. In both the US and Europe, growth in commercial traffic has led commercial airlines to request increased access to military airspace in recent years.¹

Reducing the impact of such airspace restrictions on air traffic is becoming an increasingly important issue, both due to increasing traffic levels and to an increase in the extent of SUA around the world. To address concerns about commercial space operations impacting commercial air operations, for example, the US Federal Aviation Administration (FAA) has been developing plans for an integrated Space and Air Traffic Management System for several years.² This plan includes concepts for reducing the barriers between air and space operations.

Impact Analysis

Airspace is a limited resource. No matter how dynamic or complex a separation policy may be, it must ultimately result in the allocation of airspace to each flight as needed. The specific volume and duration of space allocated to SUA are situation-dependent, based on factors including the nature of the flight operations and local airspace and traffic constraints.

Conflicts will arise whenever multiple operations demand access to the same airspace at the same time. Holding or diverting flights can safely resolve these conflicts, but may adversely impact airline schedules, operating costs, and controller workload. Hence the preferred airspace / traffic management policy will minimize such impacts while maximizing safety, efficiency, equity, and service for all users of the airspace.

But how can the adverse impacts associated with a given policy be assessed? There have been numerous analyses of specific issues of varying scope, but few offer much in the way of general theory to facilitate comparison of the impacts associated with diverse policies.

This paper presents a framework for such general assessment, based on an analytical model of airspace conflicts. The following sections will introduce the overall approach, present the analytical conflict model and its validation, and apply the approach for a first-order assessment of the impacts on air traffic associated with space-operation related SUA.

Analytical Approach

We begin by framing the adverse impacts of the conflicts as costs. A conflict is defined as an event where a given flight seeks access to a particular region of airspace, but that airspace is unavailable, being already allocated for use by some other operation. This definition implies that impact costs are a function of airspace-restricting events, which allows us to construct the following simplified abstraction representing the total annual cost, J , of airspace conflicts on air traffic for a given region of SUA:

$$J = N \cdot E \cdot D \cdot C \quad (1)$$

where N is the average number of conflicts per SUA activation event, E is the average number

of SUA events per year, D is the average impact on traffic per conflict, and C is the average cost per unit of impact.

The idea is that the average number of conflicts per SUA event times the average number of SUA events per year gives the average number of conflicts per year. This, multiplied by the average impact per conflict (e.g., minutes of additional flight time), results in the total impact per year. Finally, multiplying this by the average cost per unit impact (e.g., cost per minute of additional flight time) yields a dollar estimate for the total annual impact cost. Such an abstraction, based on aggregate averages, is unlikely to be very precise for any given problem, of course. Nevertheless, J can still be useful; its value should be valid for order-of-magnitude and sensitivity comparisons. This abstraction can also help to indicate the major factors contributing to adverse impact costs, leading to actions to mitigate these impacts.

That said, the overall calculation of J may not actually be necessary for some policy analyses. The root of the impact on air traffic is N , the number of conflicts that occur for a given SUA event. For initial studies, focusing on N may provide insight into how SUA should be allocated before requiring additional details about how delay or deviation impact accrues with conflicts, and how costs accrue with delays or deviations. Ultimately, a dollar estimate of the impact would have value for comparison with other monetary costs and benefits.

There is another important feature of N from an analytical standpoint: it is the least situation-dependent of the four factors. Regardless of the number of SUA activation events per year, or the specifics of the conflicts and the procedures used to resolve them (which heavily influence D), or the cost per unit impact, we can be confident to first order that the fewer the conflicts, the lower the total impact cost. Accordingly, for both of the above reasons, we focus here on modeling N , the average number of conflicts per SUA event, as a fundamental metric of the adverse impacts associated with an airspace / traffic management policy.

Modeling Methods

The basis of any modeling effort can be either empirical or analytical. The goal of empirical modeling is to observe system behavior in a

specific, detailed study. Empirical scenarios may be based upon either actual or artificial inputs, and they are most useful when the system behavior is too complex (or obscure) to predict theoretically.

If the relationships between system elements are sufficiently well-understood to be represented mathematically, however, an analytical model may be constructed. Analytical models are used to predict aspects of system behavior from a more global or generalized perspective. Once the large-scale effects are understood, follow-on empirical studies may be warranted to examine a specific problem in more detail.

For airspace and air traffic problems, a number of powerful empirical models have been developed. Examples such as the Total Airport and Airspace Modeler (TAAM),³ Collaborative Routing and Coordination Tools (CRCT),⁴ the Future ATM Concepts Evaluation Tool (FACET),⁵ and the Airspace Occupancy Model (AOM)⁶ are recognized as excellent for modeling specific types of problems. The study described here, however, was more about flexibility than precision, because a wide range of SUA policies and situations were to be examined.

No analytical model of airspace / traffic impact has been readily available. Gas models have been used for statistical conflict analyses of traffic flows, but airspace conflicts in particular have not been modeled in this way. Consequently, we derived an analytical model to enable these types of conflict studies.

Analytical Airspace Conflict Model

Aircraft trace out four-dimensional trajectories through space and time. Conflicts occur whenever two or more aircraft occupy the same location in that 4-D space. By extension, it is possible to identify those aircraft that will have conflicts with a given region of airspace by examining whether their 4-D trajectories pierce the volume of space-time taken up by the SUA.

Defining the problem in terms of space-time utilization enables a determination of the average number of conflicts that SUA would induce for any given pattern of background traffic – the flights that would transit the airspace in question, were it not already in use.

To illustrate the concept, consider a coalitude planar flow of air traffic encountering a circular restricted area which is active for some finite period of time, T . As shown in Figure 2, this situation can be represented by a three-dimensional space-time volume, where x and y represent spatial dimensions, and the vertical axis represents time. The SUA is shown in Fig. 2 as a circle in space projected upwards in time while it is active, forming a cylinder.

Aircraft are traveling in the x direction in space, and trace out the paths shown in Fig. 2 in space-time. Any aircraft following paths through space-time that pierce the cylinder would encounter the restricted airspace while it is active. Those aircraft will need to reroute, delay, or otherwise change their paths, and are counted as conflicts.

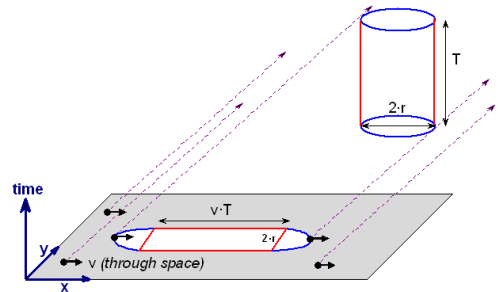


Figure 2: Example Space-Time Diagram

To find the number of conflicts, the SUA cylinder is projected onto the x - y plane along the direction of the 4-D aircraft velocity vectors. Each aircraft within the projection area will ultimately conflict with the SUA. The area of this projection multiplied by the mean traffic density then gives the number of conflicting aircraft, on average.

The projection of the SUA onto the x - y plane is shaped by four factors: the geometry of the restricted airspace, the duration for which it is restricted, aircraft velocity, and any spatial motion that the SUA region may have. If the airspace was only restricted for a moment, the cylinder in Fig. 2 collapses into a circle, and it would simply displace any aircraft in a circular area of πr^2 . So if the mean traffic density is ρ , the number of these “displacement conflicts” is $\rho(\pi r^2)$.

If the restricted area stays active for any duration, the restricted space-time cylinder gains height, which causes the projection in space to stretch laterally. In Fig. 2, this stretching

projection is rectangular in shape, and is defined by the diameter of the circle ($2r$) on its short side, and the velocity of the aircraft times the restricted duration (vT) on its long side. This represents the aircraft that are not initially displaced by the restricted area, but would fly into it while it was still active, and therefore also have to deviate. Thus the average number of “encounter conflicts” is $\rho(2rvT)$.

The sum of the displacement and encounter conflicts represents the total number of conflicts. So the complete analytical conflict model for this simple 2-D example is

$$N = \rho(\pi r^2 + 2rvT) \quad (2)$$

where ρ is the mean traffic density, r is the SUA radius, v is the mean aircraft velocity, and T is the active duration of the SUA.

General Form of the Conflict Model

The rationale used to generate Equation 2 can be extended to any geometry of SUA and to three dimensions of space. A more general form can then be obtained:

$$N = S\rho\left(1 + \frac{T}{\tau}\right) \quad (3)$$

where S is the spatial volume of SUA, ρ is the mean traffic density, T is the active duration of the SUA, and τ is the mean time for aircraft to transit the SUA. In the two-dimensional example above, $S = \pi r^2$, and $\tau = \pi r/2v$ for a circle. As in the two-dimensional example, Eq. 3 includes one component for the spatial displacement that the SUA causes regardless of its active duration ($S\rho$), and a second component which is a function of the active duration relative to the mean transit time ($S\rho T/\tau$).

Equation 3 is valid for average values of traffic density or transit time. This is a disadvantage when more specific information is available, such as a known route structure in the vicinity of the SUA. But its simplicity is an advantage in broad studies when a general understanding of the interaction between parameters is desired.

One advantage of an analytical model is that it can readily be used to perform sensitivity studies. Equation 3 shows, for example, that N is expected to increase linearly with traffic density. The relationship between N and SUA size is

more complex, because S also impacts the mean transit time, depending on the specific geometry of the SUA and the make-up of the traffic flows. If the mean SUA transit time (τ) is large relative to the duration of the SUA, then N may be insensitive to that duration ($T/\tau \ll 1$). This could occur with either slow traffic flow or very large SUA, and implies that in such conditions it may not be worth extra effort to attempt to reduce the active duration of the SUA by introducing new technologies or procedures. Conversely, with fast traffic flows, the number of conflicts becomes very sensitive to the SUA active duration, and it may be advantageous to search for policy changes that could reduce T .

Validation

To validate the analytical conflict model, Enhanced Traffic Management System (ETMS) data for the Miami Center (ZMA) over one week (March 14-21, 2001) was analyzed. The focus of this validation was the impact of activating the Kennedy Space Center (KSC) SUA shown in Fig. 1. Four distinct traffic conditions were identified within the ETMS data set. These include two temporal classifications representing variations in traffic density due to scheduling: peak or “day” (1100 to 1800 local time) and trough or “night” (0100 to 0500 local time), and two geographic classifications representing variations in traffic density due to the airway structure near KSC: “inland” and “offshore”.

The KSC SUA was not restricted during the subject week of ETMS data, which was selected to represent typical traffic conditions. MITRE’s Collaborative Routing Coordination Tools (CRCT) model was used to compute the number of conflicts that would have occurred if the SUA had been restricted. CRCT enables the user to define an arbitrary Flow Constrained Area (FCA) and to identify all the flights that encounter it while it is active. Thus CRCT was ideally suited for counting the number of flights that would have had to reroute around a given SUA size which was active for a given time. Average counts over the week (for a given time period such as day or night) were then obtained using CRCT. By varying the size and active duration of the FCA in CRCT, we could examine a range of conditions and compare them against the analytical conflict model in Eq. 3.

The average transit time, τ , was approximated by modeling the SUA as a circular region with the same area as the FCA that was used in CRCT, and using the average aircraft velocity from the ETMS data. This representation was expected to introduce little error, since the actual SUA regions were not irregular in shape. In addition to simplifying the analysis, this approach produces results that are robust to minor variations in air traffic routes.

Mean traffic density information for the four conditions (day/night, inland/offshore) was determined using a regression analysis comparing the counted number of conflicts from CRCT against Eq. 3 over several SUA duration and size conditions. A different average traffic density was then derived for each of the four traffic conditions, shown in Table 1. Given these density values, Eq. 3 fits the empirical data from CRCT within 99% confidence limits. A more complete validation would require estimating mean traffic density from a different source and then comparing CRCT against Eq. 3. Still, once the mean traffic density has been estimated, the application of Eq. 3 appears to provide an accurate estimate of conflict counts over a wide range of SUA sizes and durations while density is held roughly constant.

Table 1. Mean Traffic Density Conditions

Condition	Mean Traffic Density, ρ (aircraft per 10,000 nmi ²)
Day / Inland	19.04
Day / Offshore	4.66
Night / Inland	1.47
Night / Offshore	0.24

Figure 3 shows a comparison of empirical conflict counts (from CRCT) and estimated conflict counts (from Eq. 3) as a function of the area of an SUA that was active for 180 minutes during daytime. For example, an offshore SUA area of 23,780 nmi² (corresponding to a circular region of radius 87 nmi – approximately the size of the large SUA Warning Area in Figure 1) resulted in an average of approximately 116 conflicts in CRCT during daytime. Equation 3 predicts 121 conflicts for the same conditions.

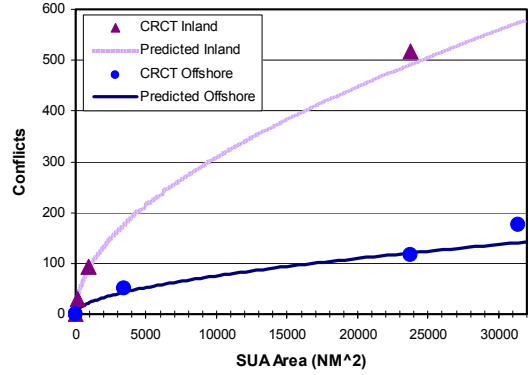


Figure 3. Conflict Count vs. SUA Area
T = 180 min, daytime

Figure 4 compares empirical and analytical conflict counts as a function of the active duration of SUA for a constant SUA size of 23,780 nmi². The empirical data show a linear relationship between conflicts and the active duration of the SUA, as Eq. 3 predicts.

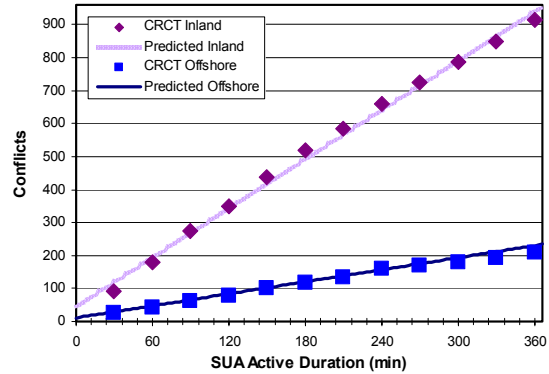


Figure 4: Conflict Count vs. SUA Duration
S = 23,780 nmi², daytime

MIT Simulation Validation

To facilitate an additional validation of Eq. 3, an empirical Monte Carlo fast-time simulation model was developed at MIT to simulate 2-D flows of air traffic. This model was used to investigate the impacts of restricted areas under various conditions and enabled analysis of the effects of traffic rerouting procedures.⁷ In the model, aircraft were randomly generated and flew along a flight corridor in the vicinity of SUA. If an aircraft was projected to be within the SUA and was within a certain distance, it was rerouted using simple conflict resolution procedures. Rerouting traffic could also conflict

with other aircraft in the area, generating secondary or induced conflicts.

Figure 5 presents a plot of the number of conflicts predicted using Eq. 3 and observed from the empirical traffic simulation for circular restricted areas of various radii. The SUA in Fig. 5 was active for 2 hours, and aircraft had a velocity of 450 kt with a mean density of 38.5 aircraft per 10,000 nmi². The observed results match the predictions within the uncertainty of the Monte Carlo simulations of 5,000 aircraft, offering additional support to the validity of the analytical model.

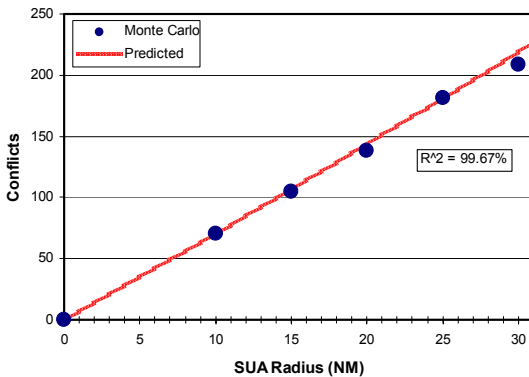


Figure 5: Monte Carlo Simulation Comparison with Analytical Model

Secondary Conflicts

Traffic that is rerouting to avoid a region of SUA may induce other, secondary conflicts with other air traffic in the area. These secondary conflicts magnify the overall traffic impact and controller workload associated with SUA.

To investigate secondary conflicts, the Monte Carlo simulation model described above was used to run simulations of a uniform traffic distribution encountering a circular SUA.⁷ Figure 6 presents one set of empirical results relating to the obstruction of the SUA in terms of the percentage of the traffic flow with conflicts. 1000 aircraft were simulated. The line with square points represents primary conflicts (N), increasing linearly with SUA radius. The three other lines represent secondary conflicts at different traffic densities. “Low,” “medium,” and “high” traffic density correspond to an average of 8, 16, and 32 aircraft per 10,000 nmi². For example, at high traffic density and an SUA radius equal to 20% of the width of the traffic

stream, approximately 40% of the aircraft had conflicts with the SUA, and 55% had conflicts with aircraft rerouting around the SUA. Thus, the impact of SUA can extend well beyond its spatial area because rerouting air traffic requires airspace that would otherwise be used by other aircraft. Figure 6 also shows that the secondary conflict effect is smaller as traffic density or the SUA size decrease. This suggests that in dense traffic areas, it will be increasingly more important to attempt to minimize SUA size to reduce traffic impacts.

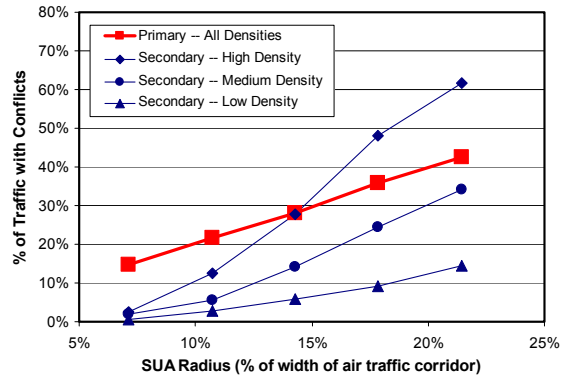


Figure 6: Secondary Conflict Effects

Transient Effects

If information regarding aircraft flight plans and the SUA is perfect, then all aircraft could be rerouted at takeoff or given ground delays to minimize in-flight costs. In practice, many aircraft are rerouted tactically around SUA, for example, when traffic comes within a certain distance of the SUA. This tactical rerouting behavior induces transient effects into the flow as aircraft begin responding to the presence of the SUA, in a similar manner to the transient effects of fluid flow in response to the sudden appearance or disappearance of an obstruction.

Using the MIT Monte Carlo simulation model, an analysis was performed to examine these transient effects when SUA is activated or deactivated. The simulation was run for 5000 randomly-generated flights encountering an SUA region with a radius of 30 nmi. Aircraft began to reroute to avoid the active SUA when they were within 100 nmi of its boundary, and/or when they would approach other aircraft within the separation standard. The number of aircraft that were currently off their original tracks at each given time, termed here the conflict load, was

then recorded. Figure 7 shows a combined plot of the conflict loads during 20 simulation runs (for a total of 5000 aircraft). The SUA was activated at $t = 0$ and deactivated at $t = 33$ min.

In Fig. 7, note that rerouting begins approximately 20 minutes before the SUA is actually restricted. These are aircraft that begin deviating in expectation of the SUA activating in front of them in their path. This precursory ramp-up of conflicts also demonstrates the cost of scrubbed activations. Even if the SUA is never activated, some traffic may be displaced in anticipation of a scheduled activation.

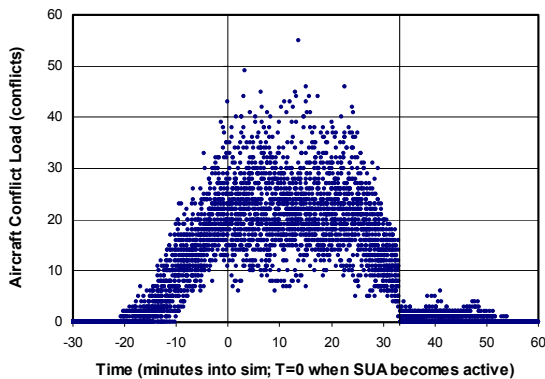


Figure 7: Transient Conflict Effects

By the time that the SUA actually becomes active, the conflict load reaches a steady state. Variability in the conflict load in Fig. 7 is due to the random nature of the Monte Carlo simulation, varying the actual traffic density and number of aircraft that needed to reroute at any given time.

When the SUA is deactivated at $t = 33$ min, there is a significant decrease in the conflict load as aircraft can immediately begin to fill the void left by the SUA and rejoin their original paths. But, it can be observed that some residual traffic conflicts continue for approximately 20 minutes after the SUA is deactivated. These conflicts are associated with aircraft attempting to reorganize and re-enter airways from which they had previously deviated, plus aircraft still affected by secondary conflicts. The lead and lag times of the conflicts is a function of the speed of the air traffic, the size of the SUA, and the methods used to reroute or deconflict traffic.

The combination of secondary conflicts and transient effects demonstrate that the impact of SUA extends beyond its actual volume both in

space and in time. These effects can currently only be examined empirically due to the complexity involved. However, additional modeling efforts are underway to extend Eq. 3 to also include these effects.

Generalized Conflict Modeling

Fundamentally, any conflict involves a situation in which a given region of space-time is desired by two or more users. The discussion to this point has focused on conflicts between moving aircraft and static airspace. Other types of conflicts can be examined from a similar general viewpoint, however.

There may be opportunities, for certain types of operations, to make the allocation of SUA more flexible or seamless. Consider space launch operations, for example. Currently, space vehicles launch vertically at high speeds, are relatively unreliable, and jettison stages that fall back to earth. All of these factors essentially require segregating a large volume of airspace to protect against the potential for a catastrophic failure or loss of control. There is no time for air traffic controllers to resolve a conflict between an aircraft and a space vehicle.

Some aerospace concepts, however, may allow for a more integrated use of the airspace.⁸ The Pegasus launch vehicle, for example, currently uses a conventional, piloted L-1011 as its first stage, enabling it to coexist with other air traffic for at least a portion of its mission profile. Other reusable launch vehicle concepts may also enable more tactical separation methods to be used during some phases of flight.

Any SUA or protected zone around an aircraft (defined by separation standards) utilizes a volume of airspace for the duration of its restriction or flight. This being the case, it would be of value to assess the sensitivity of the conflicts (and therefore conflict costs) to both the restricted airspace spatial extent and active time, and to investigate the tradeoffs between them. It would then be possible, for example, to compare operations with a fixed region of SUA, to a smaller dynamic flight corridor, to completely tactical protected zone protection as is the case with conventional air traffic.

Conclusion

This paper presents a novel analytical model that can be used to estimate the number of air traffic conflicts with an arbitrary region of restricted airspace. In this study it was applied to analyze the Special Use Airspace (SUA) associated with the US Eastern Launch Range. The user must specify SUA size and active duration, and the model also requires estimates of mean air traffic density and the mean time for traffic to transit the SUA. The use of average values for these parameters is shown to still allow accurate modeling of the number of conflicts that will occur, as demonstrated through a validation based on two empirical simulation models.

Balancing the impacts of restricting airspace with other technical factors and policy issues will become increasingly important as airspace becomes more congested and new modes of operation are implemented. Analytical models such as the one presented here will be of value for initial assessment of various airspace management options. Impact sensitivity to airspace and traffic characteristics can be determined directly, providing insight into the potential effects of options such as creating SUA in new locations, or managing existing areas differently (decreasing SUA size or active duration, for example). This approach could even be applied to real-time assessment of options for routing traffic around areas of bad weather or equipment outage.

Empirical analyses were also performed to investigate the impact-multiplying effects of secondary (induced) conflicts and the transient effects associated with SUA activation and deactivation. These dynamic effects may be important in some cases, perhaps warranting a future extension of the analytical conflict model to improve its utility.

Acknowledgments

This paper documents research undertaken by the National Center of Excellence for Aviation Operations Research, under Federal Aviation Administration Research Grant Number 96-C-001. This document has not been reviewed by the Federal Aviation Administration (FAA). Any opinions expressed herein do not necessarily reflect those of the FAA or the U.S. Department of Transportation.

The authors are appreciative of the support provided by the FAA Commercial Space Transportation Office, and in particular the guidance provided by Kelvin Coleman and Herb Bachner. We also wish to acknowledge Dr. Craig Wanke at MITRE for his valuable assistance with ETMS data and CRCT validation studies.

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References

- ¹ Nordwall, Bruce D., "Europe Takes Initial Steps Toward 'One Sky' Concept", Aviation Week and Space Technology, 26 March 2001.
- ² Concept of Operations for Commercial Space Transportation in the National Airspace System (v 1.1). Office of the Associate Administrator for Commercial Space Transportation, Federal Aviation Administration, 14 January 2000.
- ³ Odoni, Bowman, Delahaye, Deyst, Feron, Hansman, Khan, Kuchar, Pujet, and Simpson, "Existing and Required Modeling Capabilities for Evaluating ATM Systems and Concepts", MIT International Center for Air Transportation Report ICAT-98-2, March 1997.
- ⁴ Carlson, L. S., and L. R. Rhodes. Operational Concept for Traffic Management Collaborative Reroute Coordination Tools. The MITRE Corporation MP92W0000106, McLean, VA, April 1998.

⁵ Bilimoria, K. and B. Sridhar, "FACET: Future ATM Concepts Evaluation Tool", 3rd USA/Europe Air Traffic Management R&D Seminar, Naples, Italy, June 2000.

⁶ Trani, Sherali, Smith, Sale, and Quan, "Development of Airspace Sector and Encounter Models to Support the Analysis of Airspace Separation and Collision Risk", NEXTOR Research Report RR-98-16, Virginia Polytechnic Institute and State University, November 1998.

⁷ Falker, J. M., "Conflict Analysis of Air and Space Modes of Transportation", S.M. Thesis, Technology and Policy Program, Massachusetts Institute of Technology, September 1999.

⁸ Khan, K. and J. Kuchar, "Integration of Reusable Launch Vehicles into Air Traffic Management: Phase II MIT Research Final Report", NEXTOR Research Report RR-98-13, Massachusetts Institute of Technology, September 1998.