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Engineering and Policy Analysis of Strategic and Tactical Options  
for Future Aerospace Traffic Management

by

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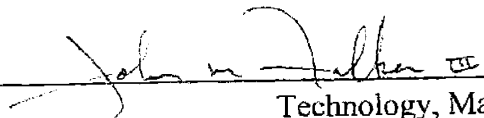
Submitted to the Engineering Systems Division  
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DOCTOR OF PHILOSOPHY IN  
AEROSPACE ENGINEERING AND POLICY ANALYSIS

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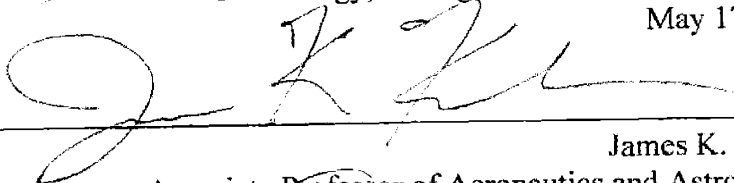
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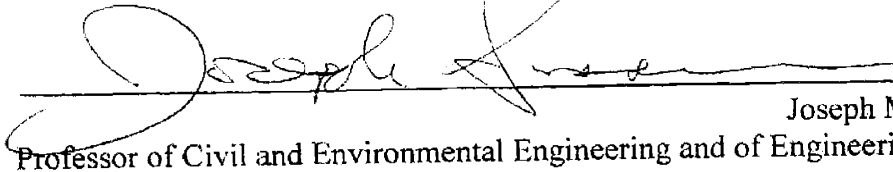


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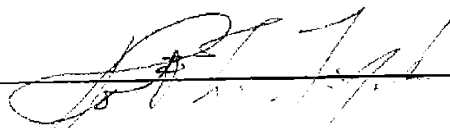
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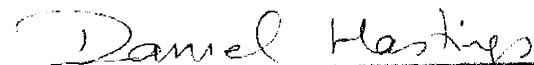


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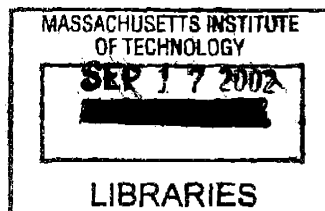


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# Engineering and Policy Analysis of Strategic and Tactical Options for Future Aerospace Traffic Management

by

John M. Falker III

*Submitted to the Engineering Systems Division on May 17, 2002  
in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy  
in Aerospace Engineering and Policy Analysis*

## Abstract

Current space launch/landing events are conducted only within Special Use Airspace (SUA), separate from air traffic. This is a strategic traffic management policy because SUA size and duration are set well in advance. It forces space operations to disrupt aviation, which could become costly with growth in air or space transportation. This was investigated through integrated engineering/policy analysis of strategic and tactical options.

Total annual disruption cost was calculated using the number of conflicts per SUA event, the annual SUA events, the average disruption per conflict, and the cost per unit disruption. The conflict count was identified as most important, and an analytical airspace conflict model was developed to predict the number of conflicts associated with restricting an arbitrary region of airspace for a given duration.

This approach was used to investigate the sensitivity of disruption cost to SUA radius, SUA active duration, air traffic density, relative velocity, annual SUA events, and conflict resolution distance. The current annual cost is under \$1 million, but the expected ranges of all factors comprise a plausible range of \$100 to \$8 million. This cost was most sensitive to SUA radius: on average, doubling the radius multiplies the cost by 49, while doubling the traffic density simply doubles the cost, and doubling the SUA active duration multiplies the cost by only 1.8. The cost was also two orders of magnitude more sensitive to "control" factors (SUA size and duration) than to "market" factors (air and space traffic levels).

Four scenarios investigated changes in multiple factors: 2% or 6% annual growth in space operations, managed by reducing only SUA radius or by reducing active duration and scheduling events to affect less air traffic. The results confirmed that radius alone is more powerful than other factors combined, and suggested that tactical alternatives could control costs over time, even with high aerospace transportation growth. However, a preliminary risk analysis indicated a safety need for large SUA, which also offers security benefits.

The final recommendations were continued use of SUA for the short-medium term, with detailed safety analysis required for future consideration of several tactical options.

Dissertation Supervisor: James K. Kuchar

Title: Associate Professor of Aeronautics and Astronautics



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# Chapter 1: Introduction

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This chapter introduces the problem of interest, describes the current air and space traffic management system, explains the motivation for this study, and presents a brief overview of the structure of this thesis.

## 1.1 At Issue

All flight operations, from ballooning to commercial aviation to space launch, require access to airspace. There exists only a limited amount of airspace, however, to be allocated among users at any point in time. Under the present system, if a region of airspace is reserved for space launch or re-entry it is closed to conventional aviation, and vice-versa. This is a conservative system prioritizing safety, but it also has implications for efficiency because one mode of operations necessarily disrupts the other.

Historically this has not been a concern, and it is not a problem today. Space transportation operations occur infrequently, and it is generally accepted that they require large buffers in space and time to ensure safety. Over time, however, continued growth in air traffic could make any given airspace restriction more disruptive, even as new reusable launch vehicles (RLVs) might lead to more frequent space operations. With such developments the present “air-or-space” traffic management policy could become increasingly expensive or restrictive, such that an alternative policy might one day become desirable.

Managing air and space traffic is the principal impetus for this research, but airspace is also restricted for many other reasons – regional security, unmanned aerial vehicle operations, scientific research, military functions, even inclement weather – so the issues are neither unique to space transportation nor limited to the United States (US). It is hoped that some of the contributions of this analysis will also be of value for these related matters.

In short, the goal of this study is to investigate the broad policy options for managing future air and space transportation within the National Airspace System (NAS). The key issues are considered, the central decision is specified, and an integrated engineering/policy analysis approach is developed and applied to compare the options and formulate recommendations despite significant uncertainty about future developments.

### **1.1.1 Focus and Scope**

In aviation, a *conflict* occurs whenever two or more flights intend to make use of overlapping regions of airspace at the same time. (In this context, “conflict” is just the standard term for such a traffic situation; it does not imply tension or hostility.) Air traffic conflicts arise frequently, necessitating the holding or rerouting of one or more aircraft so operations can continue safely. The timing of conflict resolution, like many decisions, can range from *strategic* – set well in advance and fixed for a given period of operations – to *tactical* – addressing each situation as it arises. The current aerospace traffic management policy is strategic. It is decided weeks or even months ahead of time whether a particular region of airspace will be available for air or space operations. The focus of this study is to ascertain when such strategic planning remains advantageous, and under which circumstances more tactical alternatives may become preferable.

The scope of this analysis is limited to the NAS, so all references to flight operations are meant to be atmospheric unless otherwise specified. Thus the term *space transportation* is primarily intended to distinguish space launch or landing operations – while at or below 60,000 feet – from conventional air traffic, and is not meant to include orbital or deep space operations. Finally, the term *aerospace* simply means air and/or space (as just defined) collectively, so a reference to *aerospace operations* is meant to include any vehicles flying through the airspace in question, regardless of form or function.

### **1.1.2 Research Environment**

This research is prospective. Most of the concerns that led to the initial separation of air and space operations nearly fifty years ago continue to remain valid. While integration has begun to seem more plausible with new aerospace vehicles and traffic management technologies, specific implementation decisions are complicated by sensitivity to various factors, many of which may develop over time in ways that are difficult to predict. For these reasons, calculation of the costs of the current aerospace management policy, let alone a comparison of the costs and benefits of potential alternatives, has not previously been performed. Only a few limited studies have been attempted, involving detailed modeling of specific traffic flows at particular times.<sup>1</sup> While these “point studies” have yielded precise results, their applicability to other locations and conditions has been difficult to estimate.

This thesis presents a high-level, integrated engineering and policy analysis of strategic and tactical aerospace traffic management options. At the heart of the quantitative modeling is an analytical Airspace Conflict Model, developed to facilitate rapid comparison of a wide range of policy options. This is especially useful for the preliminary analysis that decision-makers

frequently use to reduce a large range of potential actions to a few options worthy of detailed consideration – a task that was previously difficult for this application because of both the complexity of the issues and the substantial uncertainty involved.

While most of the quantitative results in this study are only first approximations, they have been validated, and they may be useful to decision-makers because not even approximations were previously available for many of these considerations. More importantly, the analytical process is transparent: the uncertainty surrounding critical factors is made explicit, and the sensitivity of the results to this uncertainty is systematically explored. This enables all conclusions to be continually refined as more information becomes available, and also helps to identify the specific pieces of information that would best improve (i.e., reduce the uncertainty surrounding) any given decision.

## **1.2 Background**

The goal of air traffic management (ATM) is to organize air traffic to accommodate multiple operations in common airspace. Ideally, good ATM policies should facilitate safe, efficient, equitable, and quality service access to airspace for all users, while accommodating growth and change over time. This section briefly describes the current ATM system, and presents some trends in air and space transportation that are relevant to the policy decision.

### ***1.2.1 Air and Space Traffic Management Today***

The US Federal Aviation Administration (FAA) manages the largest and busiest air traffic system in the world. In 2000 it accommodated nearly 40% of the world's air traffic,<sup>2</sup> including the nine busiest airports (and 25 of the top 30) in terms of total aircraft movements.<sup>3</sup> To accomplish this, the FAA employs about 50,000 people in seven major lines of business, and operates on an annual budget of over \$12 billion.<sup>4</sup> This agency establishes and implements regulations, procedures, and technical systems to facilitate all manners of operations within the NAS.

#### Air Traffic Management

All air traffic operates under either Instrument Flight Rules (IFR) or Visual Flight Rules (VFR). These are essentially separate and distinct ATM systems, run simultaneously within the NAS. IFR flights are continuously monitored by air traffic controllers, who track them on radar displays. IFR pilots must fly as directed and request clearance to change course. In this

mode, controllers are responsible for providing separation assurance from other aircraft, and flights can operate under adverse weather conditions. Large, high-performance, and commercial aircraft nearly always operate under IFR. Under VFR, in contrast, pilots can fly where they wish, subject to airspace restrictions, and each is responsible for self-separation from other aircraft (“see-and-avoid”). This mode is permitted only in clear weather, with sufficient cloud ceiling and visibility. Most general aviation (GA) traffic operates under VFR. In general, VFR flights are limited to altitudes below 18,000 feet, while IFR traffic can access airspace at higher altitudes and around major airports.

To facilitate the management of diverse operations, the FAA has divided US airspace into 22 air route traffic control centers (ARTCCs). The airspace of each center is further divided into about 20 sectors, which are generally small enough to be managed by a single controller. If traffic becomes heavy, one sector can often be split into sub-sectors so the workload for each controller remains manageable. ARTCCs primarily function in en-route control, routing and separating flights cruising between terminal areas. Traffic near terminals is often congested, so most large airports have an air traffic control tower and/or a terminal radar approach control (TRACON) to manage arriving and departing flights in the vicinity.

As well as being divided into centers and sectors, airspace is classified as one of seven types. The various classes of airspace support specific vehicles and operations, helping to facilitate safe and efficient traffic management. The seven types of airspace are:

- Class A airspace – altitudes from 18,000 to 60,000 feet, reserved for IFR operations.
- Class B, C, and D airspace – specified around major airports, large airports, and other airports with control towers, respectively.
- Class E airspace – any controlled airspace not already classified as Class A - D. This primarily applies to IFR airways below 18,000 feet.
- Class G airspace – uncontrolled airspace, available for VFR operations. In most locations this is limited to 14,500 feet or below.
- Special Use Airspace (SUA) – areas where special operations may restrict air traffic, primarily for safety reasons. Among the subcategories of SUA are prohibited areas, restricted areas, military operations areas, alert areas, warning areas, controlled firing zones, and areas under temporary flight restrictions.

In short, any region of airspace can be uncontrolled, controlled (with various stipulations), or reserved as SUA for special operations. SUA (specifically a combination of restricted areas and warning areas) is currently used to keep air traffic not involved in space operations at a safe distance. This is discussed in more detail below.

## Space Traffic Management

Every space launch or landing operation must transit the 60,000 feet of airspace immediately above the ground, however briefly, so all space transportation systems require access to the NAS. For safety, these operations are permitted only in specially defined areas of Special Use Airspace (SUA). For a variable period before and after any such operation, the SUA is activated, or restricted to air traffic. The exact restrictions are operation-specific, but a typical duration is 3½ hours.<sup>1</sup> This establishes a large temporal and spatial safety buffer between space transportation operations and the rest of the NAS. Unfortunately it can also disrupt aviation, as nearby air traffic must be re-routed around the restricted airspace.

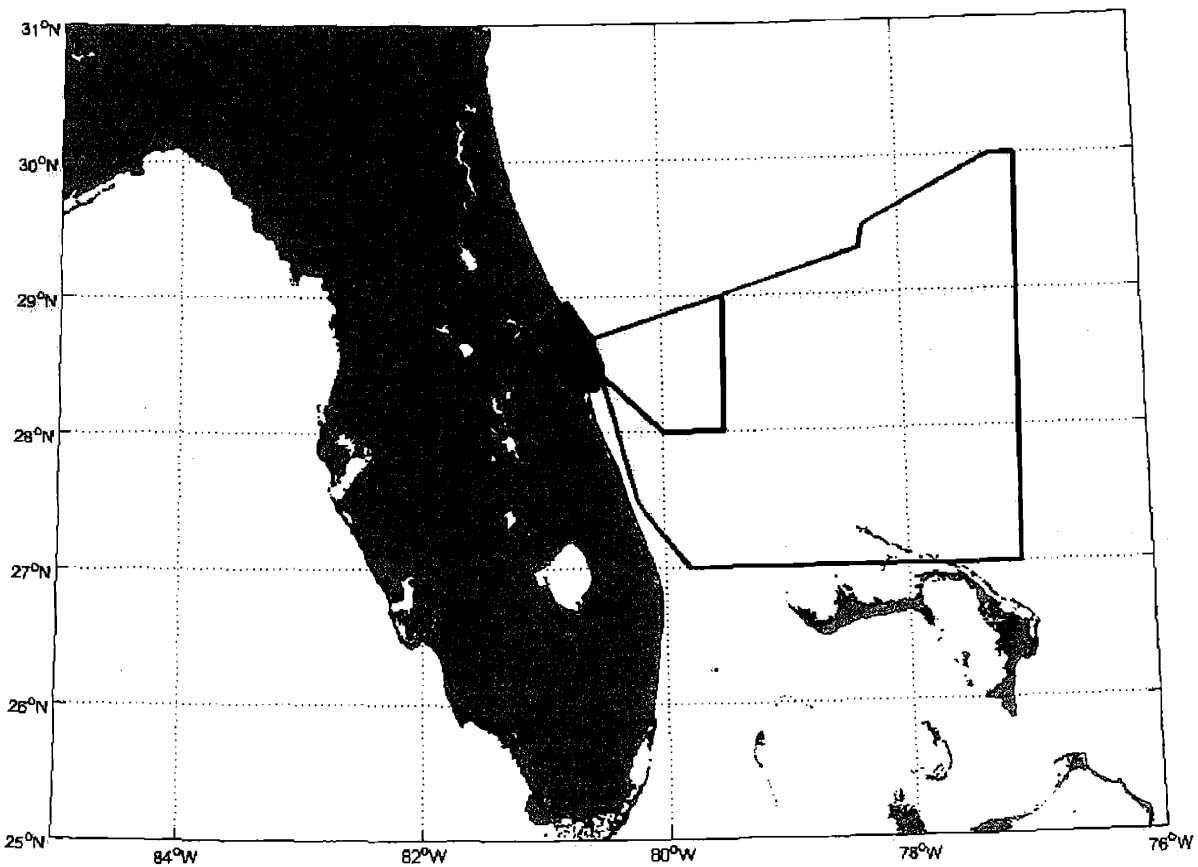
The restriction of space-related activities to SUA was a policy decision, as was the prioritization of space transportation operations over air. For many reasons, both choices were highly appropriate at the dawn of the space age:

- Most space missions were related to national security.
- Space transportation operations often had narrow, inflexible windows of opportunity.
- Spacecraft and their payloads represented enormous financial investments subject to substantial risks (early, munition-derived launch vehicles were not very reliable).
- Given the catastrophic nature of most launch vehicle failure modes, SUA was a sensible safety precaution, able to contain the vehicles, dropped stages, or debris even in the event of catastrophic failure at high speeds and altitudes.
- Finally, air traffic levels were much lower, so fewer aircraft were probably affected by any given event.

Although conservative, SUA is safe and procedurally simple. Indeed, as most of the above conditions still apply, this remains appropriate for most space transportation operations today. But there may be cause for concern about the performance of this policy under future conditions, as will be explained shortly. First, SUA is introduced in more detail.

Figure 1.1 depicts the SUA associated with the Kennedy Space Center (KSC) and the Eastern Space Launch Range in Florida. The other major US launch range is the Western Range, located at the Vandenberg Air Force Base in California. These two national ranges conduct all governmental launches and most commercial launches. There are also a few suborbital launch sites, a newly developed commercial spaceport in Alaska, and occasional commercial launches from a movable floating platform in the Pacific Ocean.





*Figure 1.1 Special Use Airspace (SUA) at the Kennedy Space Center*

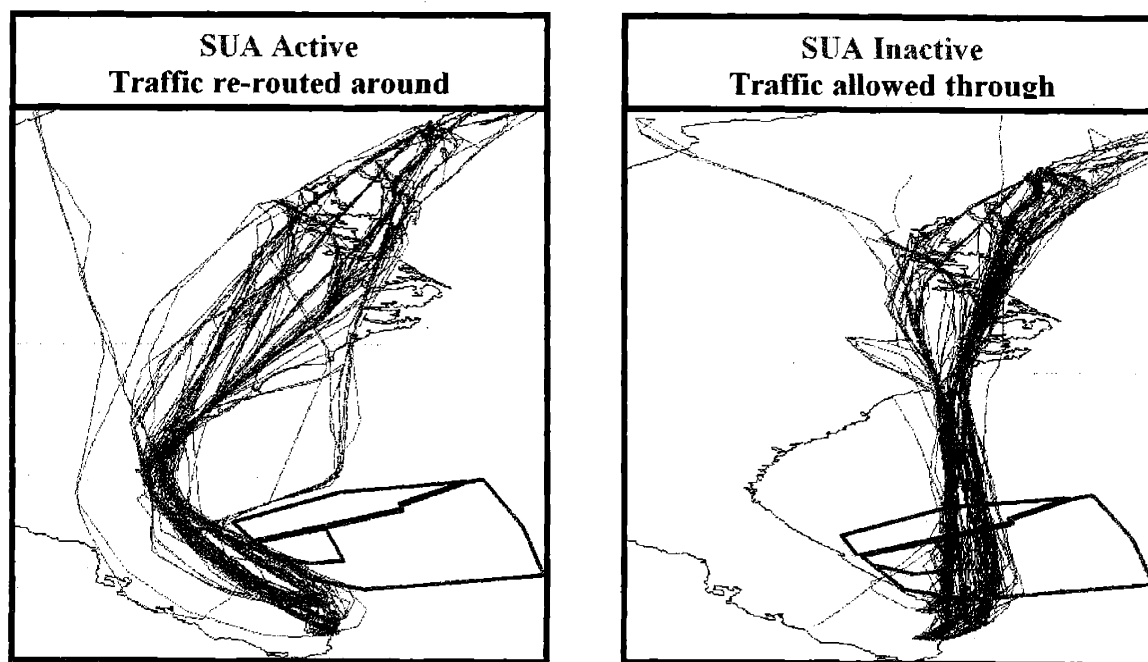
It should be clear from the figure above that this SUA covers a large area. It has almost half the total area of Florida, or over three times that of Massachusetts. A circular approximation of the same area would have a radius of about 93 nautical miles (NM), or 107 statute miles. Technically, the small inland regions are restricted areas, while the two large offshore regions are warning areas, but this distinction is immaterial; all of this SUA is restricted to all unrelated air traffic whenever there is a space operation at the Eastern Range. It is typically activated at least three hours before an operation. This provides time to ensure that the area is clear, both for the launch itself and for preliminary tests such as weather balloon launches. The airspace is generally released for use by air traffic shortly after the space operation.

It is also noteworthy that the bulk of this airspace is offshore. This is by design; vehicles launched offshore can drop stages harmlessly into the ocean as they ascend, and in the event of a failure the debris is far less likely to result in injury or harm than over land. Containment of such a failure is one reason the area is large. Another factor is that this SUA was designed to accommodate a range of eastward launches at various azimuths.

## Aerospace Traffic Management Philosophy

Two features of this air and space traffic management policy stand out. The first is that the airspace is dedicated, meaning access is allowed for only air or space operations at one time. The second is that it is strategic; the restricted size and duration of the SUA are set well in advance, rather than adjusted in response to developing circumstances. Both features contrast with conventional ATM, in that most aircraft are integrated in common airspace and separated tactically. This generally results in flights (both IFR and VFR) being disrupted only if they will soon come too close to the real-time positions of other aircraft. (Note that this refers only to conflict resolution; traffic flow management sometimes affect operations well in advance in strategic efforts to control anticipated delays.)

Allowing access to only air or space operations at one time, and allocating this access strategically instead of in response to real-time events, are both conservative decisions. Safety is vital, but it is important to realize that it is bought at the price of efficiency. This is precisely why conventional air traffic is managed differently. Disruption is costly, so traffic management procedures generally attempt to minimize this cost, while preserving safety. As shown below, the activation of SUA can be disruptive, not just to individual flights but to entire traffic flows. However, safety is paramount for space operations, and any efficiency impacts have historically been of little concern.



*Figure 1.2 Air Traffic Patterns with SUA Active and Inactive*<sup>1</sup>

Figure 1.2 shows two plots of actual flight paths, taken from a MITRE study. These plots illustrate that the activation of the KSC SUA (plus an additional northern area that is not always restricted) does in fact affect local air traffic.<sup>1</sup> The plots on the left and right track the same flights on two different days, during which the airspace is restricted and available, respectively. Clearly, a number of flights were forced to deviate. However, it is difficult to estimate how large the real impacts, such as delays, may be. Even if they are not significant at present, it would be beneficial to be able to estimate when they might become so.

To conclude this section, it is reiterated that the current policy is based on strategic separation of air and space vehicles, prioritizing safety over efficiency and space transportation operations over air. This was a logical (safe and simple) policy when instituted, still is today, and is likely to remain so, at least as long as space transportation involves sufficient risks to justify such conservative safety buffers.

### ***1.2.2 Trends in Air Transportation***

Several recent trends in air transportation are relevant to this study. Traffic growth, changes in traffic management, and promising new technologies are introduced below.

#### Air Traffic Growth

The potential growth of air traffic is of great importance for this research, because the more flights there are in the air at any given time, the greater the disruption associated with any airspace restriction. For the last 15 years, commercial air traffic has grown at an average annual rate of 3% to 4%, depending on the specific metrics examined.<sup>2,5</sup> More accurately, air traffic was growing at over 4% until 2001, when a combination of economic recession and airline-related terrorist attacks in September led to a sudden decline. Historical data for passengers flown and revenue passenger miles (total distance flown by fare passengers) are plotted in Figure 1.3. Also plotted in this figure are the 1999 FAA predictions for growth from 2000 to 2010.<sup>6</sup> Although these predictions are now a few years old, until September 2001 most other studies predicted similar growth (3% to 4% annually), in some cases all the way through 2020.<sup>7</sup> As shown, this forecast underpredicted 2000 traffic and overpredicted 2001 traffic, leaving the other predictions fairly plausible – if growth resumes. The FAA and air transport industry have recently begun to assert just this, predicting recovery in 2003 followed by 10 years of growth.<sup>8</sup> This may be a little bit optimistic, but it is probably reasonable to expect actual traffic to grow at 0% to 4% annually through 2015.

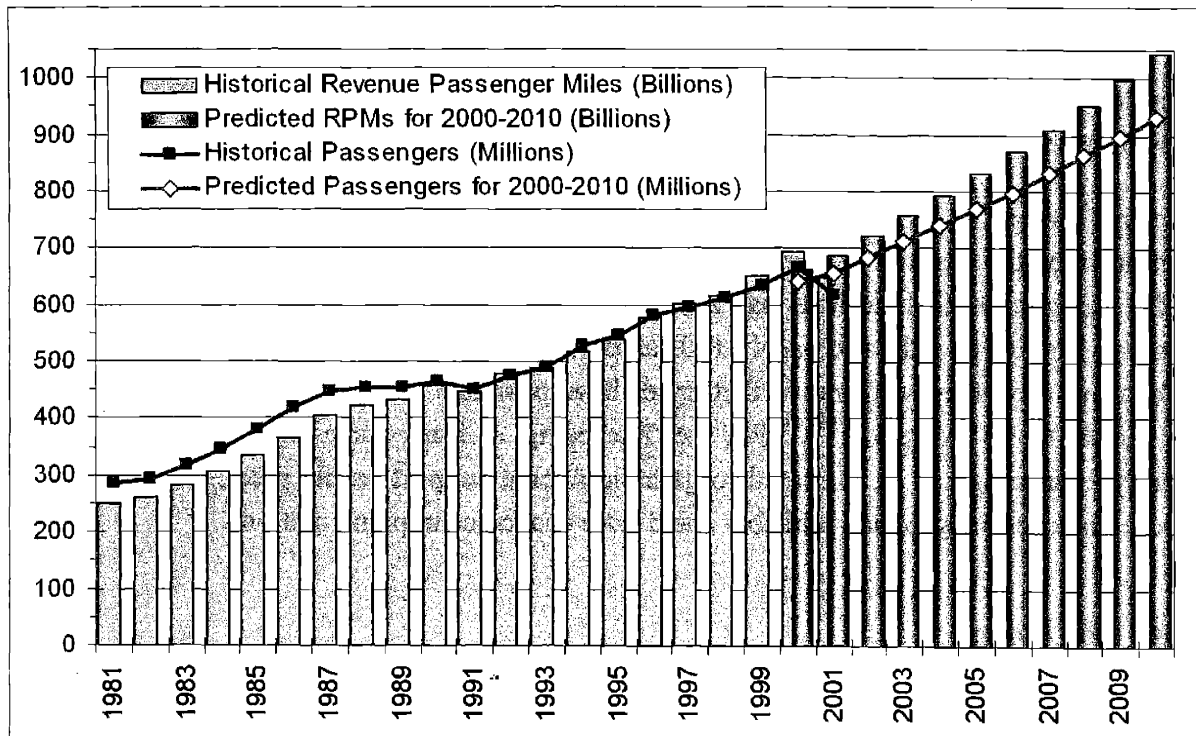


Figure 1.3 Historical and Predicted Growth in Commercial Air Traffic<sup>2, 5, 6</sup>

### Changes in Air Traffic Management

Perhaps the most important trend in ATM for this study is that toward increased freedom. The highest profile aspect of this trend is *free flight*. While the details are still unresolved, the general goal of free flight involves permitting IFR pilots to fly directly from origin to destination, or to change course at will, instead of having to (more or less) follow predefined flight plans and request clearance for any deviation. While free flight will take time to develop and fully implement, its acceptance as an operational goal has serious implications. Future air traffic patterns, especially en-route, could alter dramatically as more pilots begin flying point-to-point instead of along airways between fixed waypoints. Eventually, ATM could even become decentralized, perhaps with only a diminished role for controllers in terminal areas. At present these are merely speculations, but the potential effects of free flight may be important to consider in long-range analyses.

Other trends towards increased freedom and flexibility are also underway. The concept of dynamic resectorization – subdividing sectors to manage controller workload as traffic levels vary stochastically – has already been mentioned. Also noteworthy is collaborative decision-making. This is a trend toward changing the relationship between the FAA and airlines from that of regulator commanding the regulatees, to all participants cooperating to try to manage

operations as efficiently as possible.<sup>9</sup> Preliminary efforts in this vein have been deemed successful, and as a result the overall FAA approach is shifting from control to partnership where this is reasonable. This could affect some policy decisions, potentially facilitating or hampering the implementation of various changes.

A recent change in ATM that it is necessary to mention is the significance of security in aviation since the terrorist attacks of 2001. This is discussed further in later sections, but the public recognition that commercial airliners can be powerful weapons in the hands of terrorists has led to federal control of all aspects of aviation security, which is currently a national priority. It is well-known that crises have powerful effects on policy decisions, and this should be no exception.<sup>10, 11</sup> For the time being, at least, issues that can be framed as security-enhancing can be expected to gain significant support, while proposals that can be opposed on security grounds probably stand little chance of implementation.

### New Technologies

There are two sets of developments in aviation-related technologies that could be of interest in this analysis. The first is improvement in communications, navigation, and surveillance (CNS), especially in terms of precision. Many of the standards related to conflict resolution and traffic management have been developed conservatively, because it was historically necessary to allow for uncertainty in aircraft altitude, location, and velocity. Because of the relatively high speeds involved (typically around 450 knots for commercial airliners), small uncertainties could quickly translate into large discrepancies, requiring some standards to be quite conservative. For example, aircraft flying en-route at the same altitude are required to be separated laterally by at least 5 NM. But new technologies, such as global positioning and data-link communication systems, could significantly increase CNS precision.<sup>12</sup> In turn, this could allow smaller temporal and spatial safety buffers, potentially increasing efficiency without increasing risk.

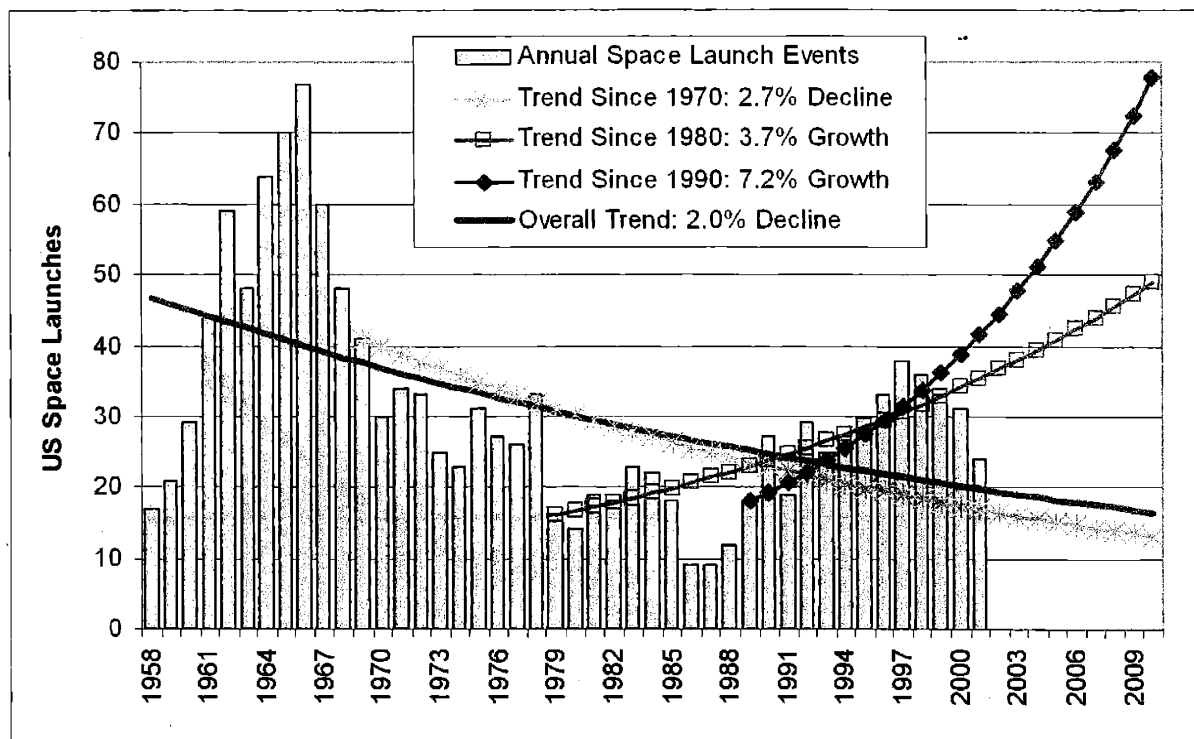
The other set of noteworthy technological developments concerns the vehicles themselves. In the short term, aircraft are not expected to differ significantly from current systems in terms of speed, size, or other basic capabilities, but unmanned aerial vehicles (UAVs) are of increasing interest. These will not replace commercial pilots in the foreseeable future, but they are growing ever more capable for a variety of applications. For example, the Predator and Global Hawk have recently been valuable in the Afghan war for reconnaissance and precision bombing.<sup>13</sup> Likewise, the nonmilitary Pathfinder-Plus and Altus are demonstrating UAV capabilities for Earth-observing science and commercial applications.<sup>14</sup> As UAVs begin flying more missions, it may be necessary to determine whether they should be integrated with other air traffic or flown in separate airspace, much like RLVs.

### 1.2.3 Trends in Space Transportation

There are also recent trends in space transportation that may bear on this analysis. Growth in operations, the development of non-governmental space transportation, and the prospect of RLVs are discussed below.

#### Space Transportation Growth

Like that of air traffic, the growth of space transportation is a critical factor in this research, because the best policy for managing only 35 launches per year may differ considerably from that for managing hundreds of operations. Historically, US space launch rates have varied widely as political and economic forces have shifted. The highest levels were achieved in the 1960s during the race to the moon. The lowest levels followed the Space Shuttle Challenger disaster in 1986. Annual US launches are plotted in Figure 1.4 below.<sup>15-17</sup>

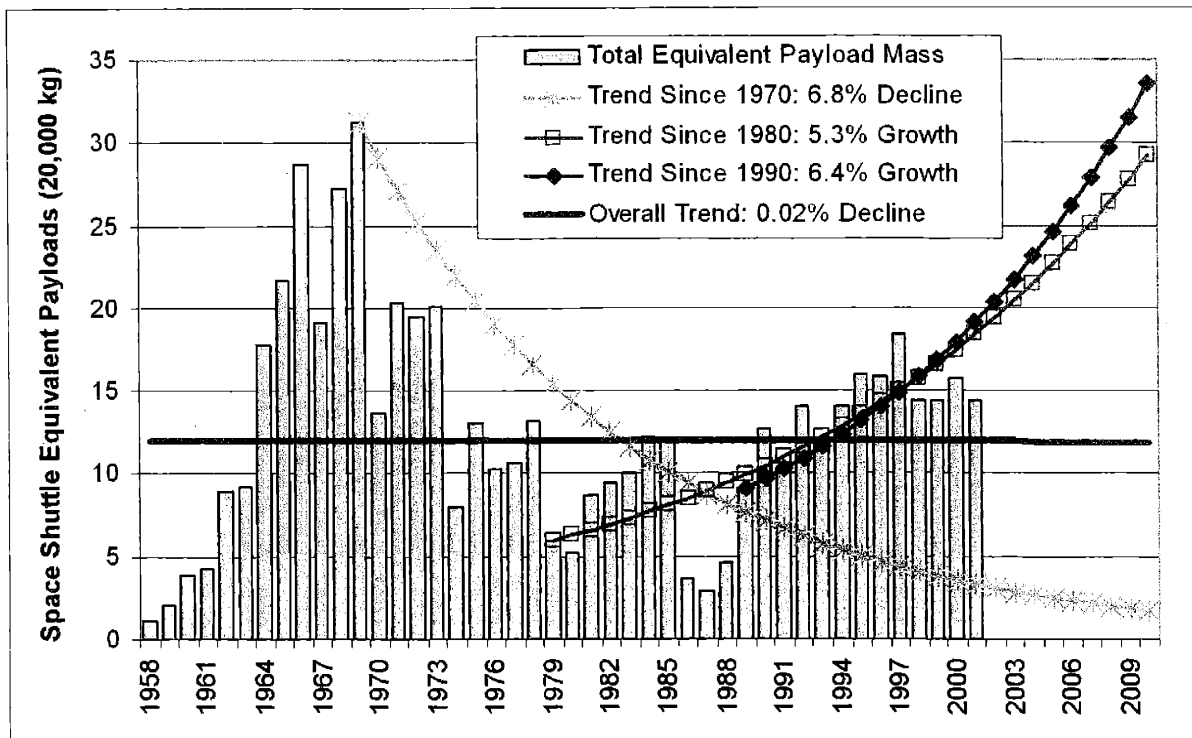


**Figure 1.4 Historical Space Transportation Trends – Launches<sup>15-17</sup>**

Unfortunately, historical trends are not particularly helpful for predicting future launch rates. Also shown in Figure 1.4 are growth/decline trends, calculated from various points in time and projected through 2010. These calculations simply start at the given year and determine the annual growth rate that fits subsequent data with the smallest sum of squared errors. This

results in the following findings: the trend since 1970 has been 2.7% annual decline; since 1980 it has been 3.7% growth; since 1990 it has been 7.2 % growth; and the overall trend is 2.0% decline. Although technically accurate, these statistics are clearly not informative; the results depend upon the arbitrary point from which the trend is measured, such that by 2010 the projections of these four trends range by a factor of five, from 13 to 78 annual space transportation events.

However, the annual number of space launches may not be the best measure of true space transportation activity, since many different launch vehicles are used. Some of these are orders of magnitude larger and more expensive than others; some are manned while most are not; and there are many other significant differences. Moreover, the set of available vehicles changes over time, so it may not be appropriate to group current launch vehicles with earlier systems and simply count launches. In light of these considerations, an alternate metric is the total payload mass transported to orbit each year. Previous studies have used Space Shuttle flights as a convenient unit for payload mass.<sup>17</sup> This is plotted in Figure 1.5, using 20,000 kg as a standard Space Shuttle equivalent payload.\*



**Figure 1.5 Historical Space Transportation Trends – Payload Mass<sup>15-17</sup>**

\* Official Space Shuttle performance is 24,400 kg to a 110 NM circular orbit at 28.5°. <sup>18</sup> Realistically, however, payload accommodation results notably in less payload mass than the baseline on most flights. <sup>17</sup> A standard of 20,000 kg produced results sufficiently consistent with those of previous studies for this application.

Also shown in Figure 1.5 are trends like those calculated for launches. Not surprisingly, the trends for payload mass are somewhat different: 6.8% decline since 1970; 5.3% growth since 1980; 6.4% growth since 1990; and almost perfectly flat overall (0.02% decline). Again however, the statistics are not very useful, resulting in 2010 projections ranging even more widely, from 2 to 34 Space Shuttle equivalent payloads.

What this really indicates is that growth/decline trends are not the proper way to analyze space transportation activity. That information must be interpreted with knowledge of the context. For example, the Apollo Program was a drive to beat the Soviets to the moon in the 1960s. It was a matter of national pride with a clear mandate and serious military/security implications. Space briefly became a top priority, receiving unprecedented resources in a surge that is unlikely to be repeated in the US in the foreseeable future. Such knowledge of the political and economic factors likely to shape the space program in coming years is needed to forecast future space transportation levels with any precision.

This type of forecasting is attempted each year for commercial launches by the Office of the Associate Administrator for Commercial Space Transportation of the FAA. They analyze the demand for satellites launched into both geosynchronous and non-geosynchronous orbits, modeling “baseline” and “robust” market scenarios. The payload projections are then used to model space transportation needs, in terms of both small and medium to heavy launch vehicles. The end result of all of this modeling for the 2001 forecasts is a series of predictions corresponding to about 3% growth per year through 2010. This growth rate applies to both geosynchronous and non-geosynchronous markets, and was found to be relatively insensitive to the investigated market variations.<sup>19</sup>

### Commercial Space Transportation

It is noteworthy that commercial space operations are worth modeling, as they did not even exist until fairly recently. The Office of Commercial Space Transportation was founded in the Department of Transportation in 1984 to “encourage, facilitate, and promote commercial space launches by the private sector” and to facilitate the expansion of the U.S. commercial space transportation industry and infrastructure. In 1995 it was transferred to the FAA, where it became the Office of the Associate Administrator for Commercial Space Transportation (AST).<sup>20</sup> Since that time AST has helped commercial space grow into an industry of respectable size. AST-licensed commercial space launches and their revenues over the last nine years are plotted in Figure 1.6 below. Both peaked in 1998 and have since declined, due to a combination of economic factors.<sup>21</sup> But as mentioned above, commercial space transportation is predicted to recover and grow through 2010.



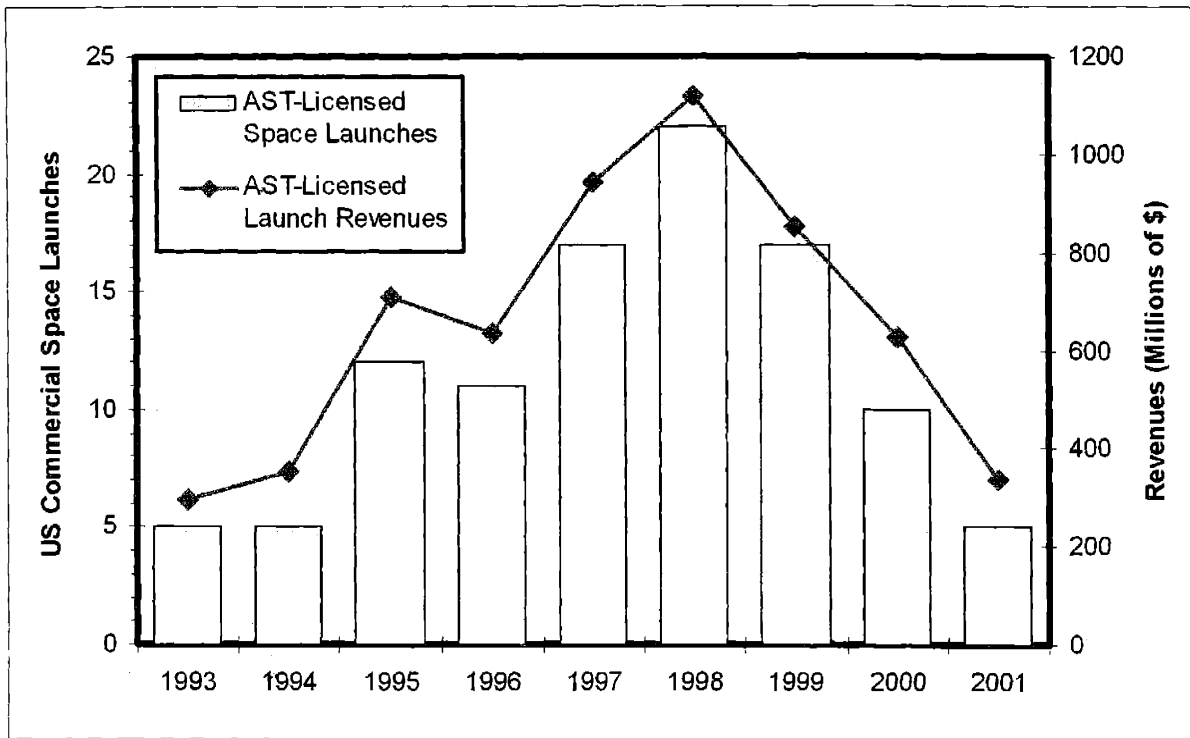


Figure 1.6 US Commercial Space Launches and Revenues, 1993-2001<sup>21</sup>

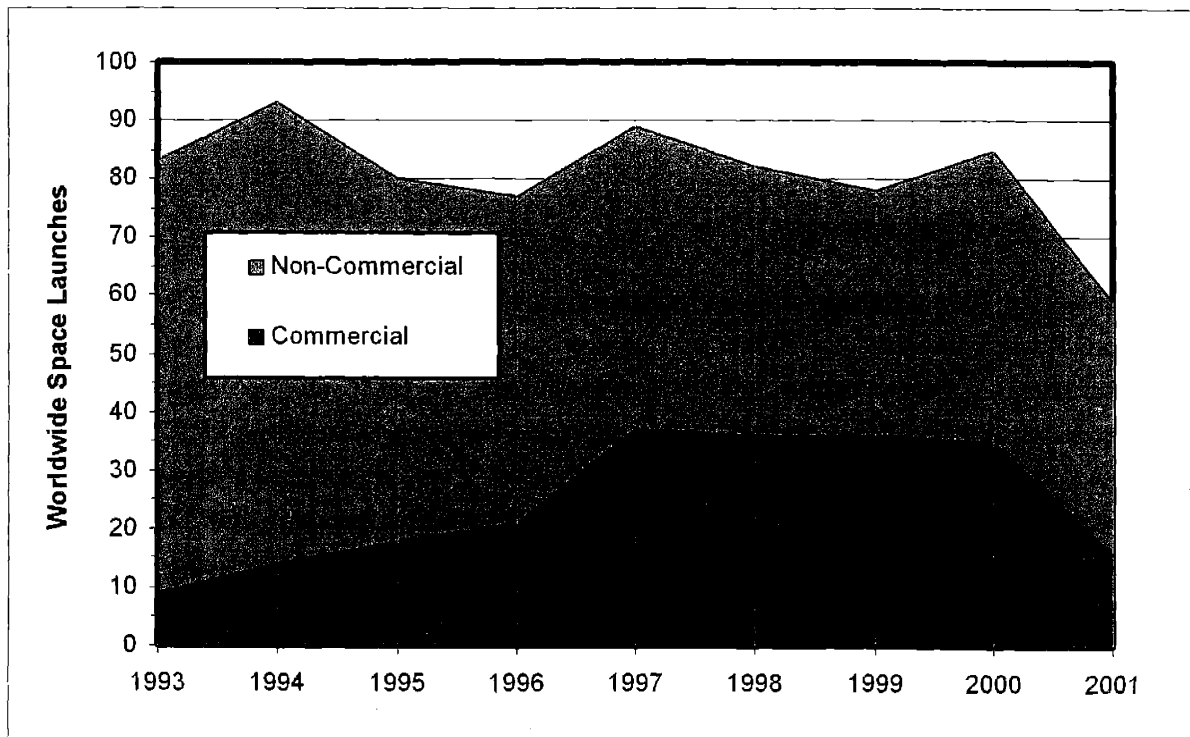


Figure 1.7 Worldwide Space Launches, Commercial and Non, 1993-2001<sup>21</sup>

Commercial space transportation is not just a US phenomenon. Figure 1.7 plots total commercial and non-commercial space launches worldwide over the past nine years. In 2001, Europe captured 50% of the commercial space transportation market, Russia and the US each captured 19%, and multinational launch consortia captured 12%.<sup>21</sup> Other nations are also beginning to compete in commercial space transportation, most notably China.

Commercial space transportation is a promising industry, despite recent declines due to adverse economic conditions. Should new launch vehicles enable more efficient access to space, as discussed below, many more commercial space ventures might be profitable, and space transportation might finally gain independence from governmental support.

### Reusable Launch Vehicles

There are fundamentally two types of space launch vehicles: expendable launch vehicles (ELVs) and reusable launch vehicles (RLVs). No true RLVs have yet been developed, but the Space Shuttle is partially reusable; the solid rocket boosters and the orbiter are recovered and reused, and only the external tank is expendable. In the short term, the principal mission for any space vehicle will simply be transportation between the ground and orbit around the Earth. This being the case, the essence of the decision between ELVs and RLVs becomes the tradeoff between initial and operational costs.

ELVs are the traditional “rockets,” which evolved from ballistic missiles. They are designed simply to achieve orbital velocity and survive to insert their payloads into orbit. An ELV usually consists of a series of stages that burn until exhausted, propelling themselves and the rest of the vehicle along a leg of the trajectory, and then disconnecting. Since the stages will not be recovered, ELVs are designed to be as inexpensive as possible. Unfortunately, each ELV still costs millions of dollars (transporting payload at about \$10,000 per pound to orbit), and is usable only once. Furthermore, the failure rate of ELVs is on the order of 1 in 100, instead of one in millions as is desired for most transportation systems.<sup>22</sup>

RLVs represent an attempt to eliminate the “waste” associated with ELVs. The intent is to develop a much sturdier vehicle that will return after transporting its payload to orbit, so it may be used repeatedly. RLVs will clearly be much more expensive to build than ELVs. An RLV must be sophisticated enough to return and land, with enough heat shielding to reliably survive multiple launches and re-entries. These modifications will make RLVs heavier, therefore requiring more thrust, which means more fuel and possibly larger engines. Hence, RLVs will probably involve higher operating costs, and also maintenance costs. But the basic idea behind the RLV is that all of these costs could be amortized over many flights, so that overall it would be more cost efficient than an ELV.

There was a serious effort in the last few years to develop single-stage-to-orbit RLVs, but a series of test programs (notably the X-33 and X-34 advanced technology demonstrators) proved these still beyond our capability to develop efficiently. With future materials and innovations in propulsion these may become advantageous, but the current Space Launch Initiative is focused on the development of the directly feasible systems offering moderate improvements in safety and efficiency. These so-called 2<sup>nd</sup> Generation RLVs are intended to achieve failure rates below 1 in 10,000, and costs below \$1,000 per pound to orbit.<sup>23</sup>

Subsequent systems may be more radical, taking advantage of advanced propulsion concepts: supersonic combustion ramjets, magnetic levitation, and even microwave or laser powered "lightcraft." These advances promise to enable access to space "100 times cheaper and 10,000 times safer than today's launch vehicles" for 3<sup>rd</sup> Generation RLVs, or "20,000 times safer and 1,000 times cheaper than today's systems" for 4<sup>th</sup> Generation RLVs.<sup>24</sup> Any such progress could quickly transform spaceflight from a risky, expensive, special event into a routine mode of transportation, as happened with aviation in the 20<sup>th</sup> century.

### **1.3 Motivation**

This section describes the potential concerns about the current air and space traffic management policy that motivated this research. The three major contributing factors are efficiency, equity, and RLVs.

#### ***1.3.1 Growth and Efficiency***

As explained in section 1.2.2, commercial air traffic levels have historically risen at about 4% per year. Before September 2001, this growth was widely expected to result in at least 50% more passengers flying by 2010 than there were in 1999. This was a grave prospect, because the summers of 1999 and 2000 each brought unprecedented delays, naturally accompanied by commensurate traveler dissatisfaction.<sup>25</sup> The decline of 2001 may have bought a little more time, but as explained, experts are already predicting recovery and resumed growth.

The major bottlenecks today are at terminals, but even if these can be alleviated, the available airspace in the NAS will remain fixed. This means that sooner or later, continued growth will make managing conventional air traffic alone problematic. If this happens, restricting large regions of airspace for any reason will become increasingly costly.

At the same time, growth in commercial space transportation is also predicted. At the least, this would result in existing SUA being restricted more often. It could even result in SUA expansion or the creation of new space-related SUA in various locations. Fourteen states recently joined to create the National Coalition of Spaceport States, with the purpose of expanding the Space Launch Initiative to include work on space transportation infrastructure (i.e., new spaceports) in each state. Any of these developments would restrict more airspace, increasing air traffic disruption.<sup>26</sup>

At some point, therefore, SUA will no longer be viable in the NAS for efficiency reasons. That will leave only two alternatives: to relegate space operations to remote locations, or to implement a policy somehow enabling simultaneous growth in air and space traffic.

### ***1.3.2 Equitable Access and Cost Distribution***

The growth of commercial space operations in recent years gives rise to a new consideration in space transportation: equity. Airlines are willing to bear the costs of deviating around SUA that is activated to support missions of national priority, but that no longer applies to many space missions. Nevertheless, these operations continue to receive priority access to US airspace, activating SUA as needed. But such restrictions impose costs on the would-be users who are denied access to the airspace. In essence, this amounts to forcing one form of commercial transportation to subsidize another.

Such an inequitable arrangement would be worthy of scrutiny in any case, but as commercial aviation is particularly competitive and associated with very thin profit margins, it could become crucial. Hence, if the continued prioritization of space makes sense for technical or operational reasons, perhaps the users who are denied access should be compensated for some of the impacts of SUA upon their operations. On the other hand, just because aviation came first does not necessarily mean it deserves priority. To be fair, the fledgling commercial space transportation industry is hardly known for profit either. Unfortunately, there is no obvious solution. If air and space transportation remain mutually exclusive, however, these equity matters must be addressed.

### ***1.3.3 Reusable Launch Vehicles***

The final set of concerns about the current policy relates to the possible advent of RLVs. The allure of the RLV is simple: building a reusable vehicle once is more efficient than building even a cheap vehicle for every flight. This is not a new idea – Tsiolkowsky, Goddard, Sänger, and other pioneers of rocketry struggled with a variety of spaceplane designs before

1930 – but there are reasons to believe that RLVs may finally be feasible in the near future.<sup>22</sup> Some reasons are technical: new composite materials with improved thermal and mechanical properties, scramjet designs that could enable air-breathing up to Mach 25, and further advancements in computational fluid dynamics modeling. Yet one is economic: although developing an RLV will be expensive, the fact that commercial space transportation has already arisen is proof that an RLV offering increased service and reliability for lower prices would be profitable. As a result, it is plausible that RLVs could soon be developed. If they are, they could enable tremendous growth in space transportation. At the same time, however, they would probably fly in the NAS longer, more often, in more locations, for more kinds of operations, which could exacerbate all of the above concerns with SUA.

#### **1.3.4 Synopsis**

Growth in commercial space transportation and especially the development of RLVs are likely to increase both the frequency and duration of SUA events. Meanwhile, the costs of any airspace restriction can be expected to rise simply because of growth in air traffic. The combination could quickly become unacceptably costly and/or operationally restrictive.

Accordingly, the first goal of this research is *problem analysis*. It is necessary to identify the major factors affecting the impacts of SUA restriction on air traffic, and to investigate the sensitivity of the impacts to changes in them. This enables assessment of the seriousness of the problem, both in the short term and with potential future developments.

The second goal of this research is *policy analysis*. This involves identifying a few plausible policy options and determining the circumstances under which each is likely to be beneficial. This information can be used to identify the policy decision that appears best with the information currently available, as well as clarifying how new developments or information could change that decision.

### **1.4 Overview**

This concludes Chapter 1, which was intended to introduce the problem, explain how air and space operations are currently managed, and discuss the motivation for this research.

Chapter 2 presents a general methodology for structuring an integrated engineering and policy analysis, and applies it to develop the analytical approach exercised in this study.

Chapter 3 focuses on the significance of conflicts and the derivation, illustration, and validation of the Airspace Conflict Model.

Chapter 4 details the technical analysis, investigating the range and sensitivity of critical factors, assessing specific scenarios, and describing the implications for the policy decision.

Chapter 5 completes the policy analysis, combining stakeholder positions and other political considerations with the results of Chapter 4 to formulate practical recommendations.

Lastly, Chapter 6 summarizes the final policy recommendations, the contributions of this research, and suggestions for future work.



## Chapter 2: Analytical Approach

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This chapter introduces complex systems, such as addressed in this study, and a general procedure for the integrated engineering/policy analysis of such problems. It then applies this procedure to develop the analytical approach exercised in the subsequent chapters.

### 2.1 Complex Systems

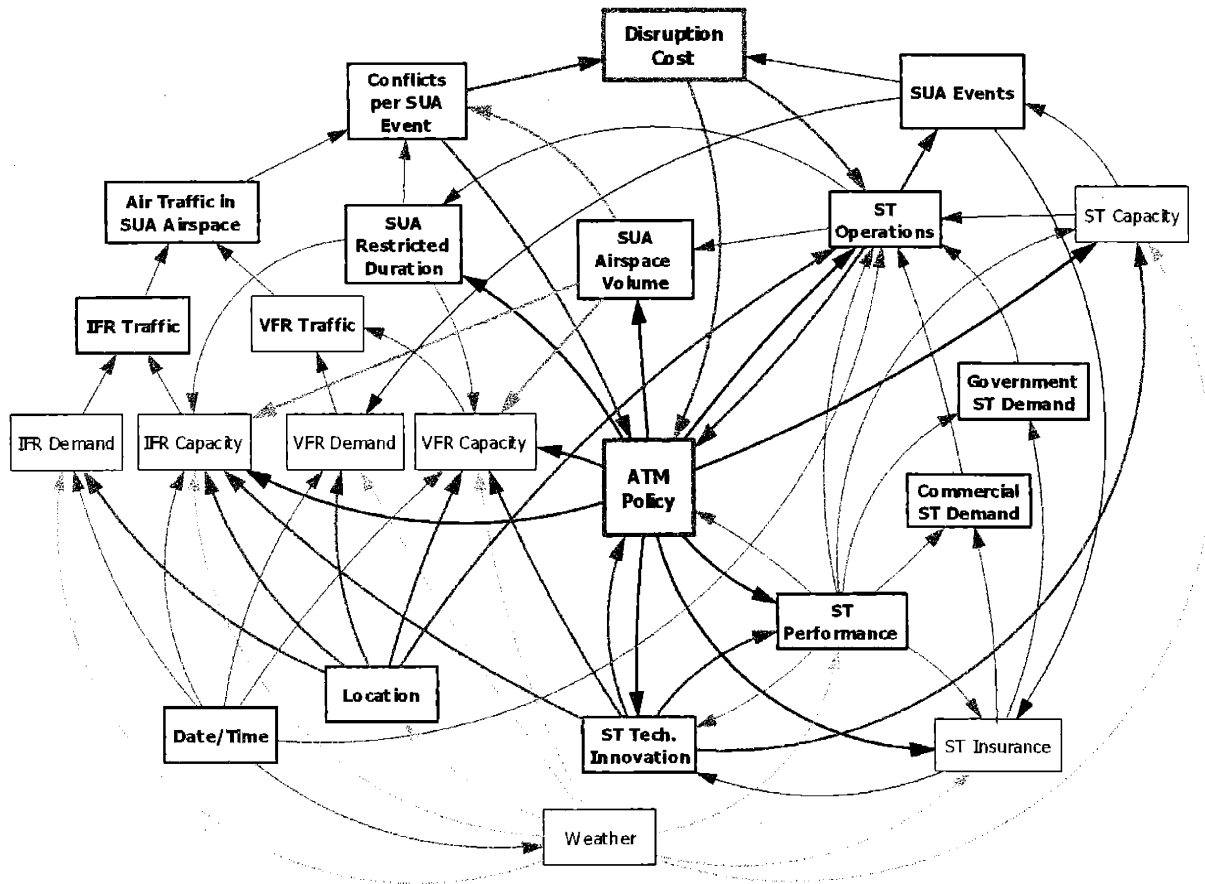
Analysis of the air and space traffic management system is complicated by the number, scale, diversity, and complexity of the elements involved, many of which are themselves complex systems. Consider the following examples:

- Vehicles – modern aircraft are expensive, sophisticated machines requiring special training and certification to operate and maintain. Designed for a wide variety of applications, non-military aircraft range in passenger capacity from 0 to over 500, and in performance (typical cruising speed and altitude) from 60 knots at sea level to 550 knots at 35,000 feet. At the extremes, balloons often fly at 0 knots and negligible altitudes, while supersonic aircraft like the SR-71 Blackbird can cruise at over 1,900 knots and 85,000 feet. (In orbit, which is in no way comparable to atmospheric flight, the Space Shuttle can approach 15,000 knots at over 1,000,000 feet.)
- Organizations – commercial airlines attempt to manage passengers, cargo, vehicles, crews, equipment, and supplies in an ever-changing environment subject to the weather and equally capricious political and economic forces around the world. There are also national and international regulatory bodies, labor (pilot, crew, construction, and maintenance) unions, military forces, port authorities, weather services, and a host of commercial entities supplying other associated goods and services.
- Infrastructure – aerospace terminals are interfaces between at least two and possibly as many as five modes of transportation (air, space, sea, road, and rail). Preferably close to urban centers for convenient access – but not too close for noise, real estate, and safety reasons – they are commonly owned and operated by a combination of public and private entities with various interests. There are also control towers, terminal radar approach control (TRACON) stations, satellite systems, radar stations, en-route centers, weather stations, and numerous information technology systems.
- Regulation – in addition to trying to oversee all of the above, regulators must strive to establish policies that are compatible with those of other nations, to facilitate both US operations abroad and international operations in US airspace.



These examples illustrate that planning for future air and space traffic management is a prime example of dealing with what Joseph Sussman has called Complex, Large-Scale, Integrated, Open Systems (CLIOS).<sup>27, 28</sup>

Figure 2.1, below, was constructed to identify the important factors in the aerospace traffic management CLIOS, and to clarify the major relationships between them. It also serves as a graphical testament to the complexity of this system.



**Figure 2.1 Aerospace Traffic Management Engineering/Policy System Diagram**

The major elements of this diagram are worth examining. Near the center is a box labeled “ATM Policy,” which in this case refers to air and space traffic management policy collectively. On the left is the air traffic of interest, affected by demand and capacity for both Instrument Flight Rules (IFR) and Visual Flight Rules (VFR) traffic. As noted in Chapter 1, IFR traffic is under positive control while VFR traffic is autonomous, so these populations behave differently. On the right are space transportation (ST) operations, affected by ST demand and capacity. Here commercial and governmental demand are distinguished because different forces affect their missions, frequencies, and priorities. Across the bottom of Figure

2.1 are other important factors affecting air and/or space operations, such as location, weather, technical innovation, and insurance. Finally the two sides come together: Special Use Airspace (SUA) is restricted for space transportation events (upper-right); this causes conflicts with local air traffic (upper-left); and resolving these conflicts disrupts the air traffic and therefore imposes a cost – the “Disruption Cost” box at the top.

For this analysis ATM Policy is an independent variable – various policy options could be implemented – and Disruption Cost is a dependent variable – the desired outcome is to decrease disruption costs. Naturally, many aspects of the system may be of interest, and other elements of the CLIOS certainly could be selected as independent and dependent variables. A method for deciding where to focus is presented in the next section, and the reasoning leading to the choices identified above is described in section 2.3. But it is not enough to decide what outcomes are desired and which parameters may be of interest; the relationships between key elements must be understood so proper actions can be planned.

Unfortunately, the connections between causes and effects in a CLIOS are generally obscure, often because of feedback loops. Such loops can quickly result in nonlinear effects and complicated behavior, so it is critical to include them when attempting to model the system. Many feedback loops can be identified in Figure 2.1. The simplest involve only two elements. For example, ATM Policy affects “ST Performance” (broadly including all space transportation systems), while various aspects of ST Performance in turn affect ATM Policy. A recent policy decision to limit the annual Space Shuttle launches literally dictates an aspect of ST performance. On the other hand, if modifications to the Shuttle were to increase safety and efficiency, policy decisions about which missions can use the Shuttle might be revised. Many more complex loops can be traced; numerous subtle relationships probably exist that are not shown. In the process of constructing this diagram it quickly became apparent that the overall system was far too complex to model quantitatively with any significant precision. The system diagram is still valuable, however, for illustrating how technical, operational, economic, and political factors are all involved. The process of constructing it enhances understanding of the issues at stake, and the diagram in itself can facilitate decisions about which aspects to investigate in detail.

CLIOS problems can be daunting. Their complexity makes them difficult to model, and their open nature – incorporating disparate external factors, such as social or political issues in otherwise predominantly technical problems – can complicate decisions with additional (sometimes opposing) values or preferences. However, this is exactly when an integrated engineering and policy analysis, properly bounded to remain feasible, may be most appropriate. This approach is explained below.

## 2.2 Integrated Analysis

Engineering analysis involves modeling the mechanics underlying system behavior, and is often concerned with technological capabilities and limits. Policy analysis involves assessing costs and benefits to formulate and implement policies for communities. It is often concerned with diverse stakeholder values and preferences. The goal (and art) of integrated analysis is to apply an appropriate combination of both to the problem at hand.<sup>29</sup>

There is no one “best” process for conducting an integrated analysis of CLIOS problems, mainly because various analytical techniques can be more or less appropriate for different aspects of a range of problems. However, a general procedure for developing a feasible approach to analyze an appropriate part of the problem involves four steps:<sup>30-32</sup>

- Identify the main decision.
- Investigate the key issues.
- Determine what information is required to resolve the decision.
- Structure an appropriate analysis to gain (at least some of) that information.

These steps are not necessarily followed in order, and are rarely completed in one pass. Instead the process is usually iterative, with many mini-loops between steps to clarify related issues. Although indirect and potentially time-consuming, this is often necessary for CLIOS, which tend to reveal new facets of problems as progress is made. The four steps are briefly explained below, and then applied in the next section.

The first step is to identify the main policy decision. The nature of CLIOS can make it difficult to single out one problem among the many issues probably involved, but analytically resolving several CLIOS decisions simultaneously is frequently infeasible. As a result, it is generally advisable to start by narrowing the problem down to the single decision thought to be most important. Not only is a single matter more likely to be analytically tractable, but any progress is likely to have implications for related decisions.

That said, the central decision is rarely obvious. It is frequently necessary to investigate various aspects of the problem in order to clarify the key issues at stake. This second step is critical when dealing with CLIOS. Insufficient understanding of how integrated aspects of the problem affect each other can lead to an apparently good solution that exacerbates other problems, or perhaps gains temporary benefits with ultimately greater long-term costs. Therefore investigation should generally continue until the central decision and the key issues reflecting major stakeholder interests can be articulated. This marks significant progress: despite its complexity, the problem of interest has become well-characterized.

It is then possible to proceed to the third step and determine what information is needed to make a decision. Typically, more information is desired than can be obtained within the constraints of time and available resources. As a result, it becomes necessary to weigh the anticipated effort/cost of the potential avenues of research against the value of the information they are expected to obtain. This begins to blur into the fourth step. Like the earlier steps, these are often iterated, exploring the potential advantages and disadvantages associated with various options. The final structure should define the feasible combination of analyses expected to best facilitate resolving the main decision.

A final note: any process of reducing a general problem to a more manageable sub-problem is not optimizing over the complete decision space; the above procedure seeks only a “good” solution, not the global optimum. This is just a practical limitation of CLIOS problems. They are so large and complex that most analysis is usually piecemeal, through specialized studies. By comparison, it is hoped that this approach – investigating social, technical, political, and economic issues in order to formulate a suitable analytical approach – represents a step closer to comprehensive analysis.

## **2.3 Developing This Study**

Using the procedure described above, an integrated analysis approach was developed for the problem (introduced in Chapter 1) of managing future air and space traffic, potentially including reusable launch vehicles (RLVs), in the National Airspace System (NAS). The remainder of this chapter presents this approach. (See Chapters 4 - 5 for results.)

### ***2.3.1 Main Decision***

Recall that the current policy is based on the strategic use of Special Use Airspace (SUA) to keep air and space operations separate. Restricting airspace to create a large safety buffer in this way reduces risks, but it also disrupts local air traffic. Two particular features of this policy are noteworthy. First, since one mode of operations (air or space) is denied access to the airspace at any given time, some disruption is unavoidable.\* Second, because the SUA geometry and activation are defined strategically instead of adjusting to changing conditions, they must be conservative (designed to ensure safety across a variety of circumstances), so the disruption associated with some specific operations may be greater than necessary. The

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\* Exceptions to this exist in remote areas (e.g., over the Pacific Ocean) with evident intervals between flights. But the NAS, including the Eastern and Western Space Launch Ranges, supports regular air traffic at all hours (late night flights are mostly cargo) and therefore upholds this assumption.

total annual cost of this disruption is unknown, but even if it not large at present, there is cause for concern that it is likely to increase over time, especially if RLVs are developed. This was discussed in Chapter 1 as the motivation for this study.

If the heart of the problem is traffic disruption arising from strategic separation, then the logical alternative is tactical separation. This would enable the integration of air and space operations in common airspace, while ensuring safety by keeping the individual vehicles sufficiently separated, as is done today with IFR traffic. Some disruption would still arise from vehicle-vehicle conflicts, but compared with SUA conflicts it is expected these would be fewer in number and involve less disruption per conflict to resolve (smaller deviations are required to avoid vehicles than SUA). Together these effects could dramatically reduce the total disruption. Just how dramatically has not been previously investigated. Furthermore, it is not even certain that there would be real benefits once safety, uncertainty, and other factors are adequately taken into account. Hence the main decision:

**Should air and space transportation be separated strategically or tactically  
in order to minimize the disruption of aerospace traffic operations?**

The primary goal of this study is to answer this question. To structure an analysis to address it effectively, the main issues at stake must be considered.

### ***2.3.2 Key Issues***

At the heart of every major transportation decision studied by the author have been tradeoffs among various combinations of four key issues: safety, efficiency, equity, and service. This assertion requires broadly defining safety as preventing harm, so it includes security and environmental interests as well as protecting passengers/property from injury/damage. But the other issues are straightforward: efficiency refers to using resources with minimal waste; equity involves fairness and justice; and service reflects how well customer needs are met (e.g., convenience, comfort). In order to indicate the kinds of information needed to resolve the main decision, each of these issues is considered below.

#### Safety

Safety has always been the highest priority of the Federal Aviation Administration (FAA). In fact, every ATM policy proposal must address safety to be worthy of consideration. Likewise, safety has always been critical in space transportation, involving as it does vehicles derived from ballistic missiles and operations frequently related to national security.

However, safety gained unprecedented importance after September 2001. The terrorist attacks affected many organizations and industries, but since hijacked commercial airliners were the means of destruction, it is almost certain that aviation has been affected most of all. Security is now a top FAA priority – indeed, aviation security is a top national priority – and the FAA is in the process of assessing weaknesses and making improvements in diverse aspects of air transportation. Amongst all of this, however, en-route traffic management is not an especial concern. No relevant changes have been suggested, so security remains not operationally distinct from the broad construct of safety already included in this analysis. However, security has become a much more important policy consideration (Chapter 5) that could lend tremendous force to conservative, safety-related arguments.

Despite the prominence of safety in air and space transportation, both in general and since the terrorist attacks, it must be emphasized that the safety (including security) of the current SUA is not in doubt. On the contrary, the question is whether it may be too conservative in some cases. The principal advantages of more tactical alternatives to SUA would be in other areas, such as efficiency. As far as safety they would primarily try to meet standards indicating operations would remain “safe enough.” This means that despite its great importance, safety is unlikely to drive this policy decision so much as constrain it.

A term for being merely good enough in one area in order to focus on another is *satisficing*. This is a common practice in multidimensional policy decisions, wherein analyzing more than a few important facets is often impractical.<sup>32</sup> In this decision safety cannot be ignored, but if it can be satisfied, a different issue will probably become the deciding factor.

### Efficiency

After safety, efficiency is generally the most important issue. Various aspects of efficiency are critical to commercial transportation service providers trying to operate under severe constraints: cutthroat price competition forces minimal profit margins on air carriers; a deep gravity well forces minimal performance margins (payload mass) on space launchers. Aircraft fly at different speeds and altitudes for engine efficiency. Organizations rearrange their structures for more efficient communication and operations. If examined closely, however, the majority of efficiency concerns ultimately boil down to costs and budgets. This implies that if SUA disruption does grow to the point of significant costs or operational interference, airlines can be expected to protest vociferously, and begin lobbying for either a change in policy and/or a system for remuneration.

A refreshingly different aspect of efficiency involves regulators attempting to help the public make the best use of common resources through better policy-making. Unlike safety this is

rarely directly mandated by law, but its importance is clear. The FAA is trying to maximize both user access to airspace and operational efficiency within it. These efficiency concerns may also be a factor in considering alternative aerospace traffic management options.

Finally, even the main decision presented above is based on efficiency: disruption (a measure of inefficiency) was identified as the main undesirable condition to be minimized by the best policy option. Therefore efficiency is certain to be a major consideration.

### Equity

Equity, especially as pertaining to the distribution of either access to airspace or the cost of denied access, is a relatively new consideration. It was initially absent because of the conditions under which space transportation arose. Early in the Cold War, with the Russians having beaten the US into space, all-space related operations were extremely high priority, high risk, high cost operations, compared with which routine air traffic was no matter. In addition, space transportation events occurred relatively infrequently and there was much less air traffic to affect, so even if disruption had been a concern it would have been negligible.

Over time, however, the situation has gradually changed. There are now almost as many commercial space operations as governmental, and priority, risk, and cost are all declining (though risk and cost not as quickly as hoped). It is no longer clear whether airlines should automatically have to yield access to airspace, or at least bear all costs of doing so. For a purely commercial launch, this is effectively requiring one form of commercial transportation to subsidize another – which the already price-sensitive airlines may not be able to bear if the disruption grows. If RLVs were to begin frequent operations, for example, airlines might be forced to abandon routes near SUA. On the other hand, space transportation actually *is* rocket science. The high precision transportation of an extremely delicate payload, worth hundreds of millions of dollars, to orbit through a launch window possibly only a few minutes wide is still a feat few nations on earth can duplicate. The notion of such operations having to yield to routine air traffic in any way may still be derisory.

Fortunately, almost any of these inequities could be redressed financially. For instance, if it were found to be safest and most efficient to continue using SUA (fully prioritizing space transportation over air), space users could be charged a fee based on the imposed disruption, and this fee could be distributed to reimburse the aggrieved. In short, though it can be argued that equity is becoming a consideration, it is still not as important as safety or efficiency, and provided the costs are not too high, it can be remedied after the fact. Consequently, it is doubtful that equity will significantly affect the policy decision.

## Service

The final issue is service, which is often traded off against efficiency in transportation systems. In design, putting fewer seats on a vehicle results in more room per traveler (better service in terms of comfort), but limits the cabin capacity to fewer passengers per trip (less efficient as a transportation system). In use, customers face similar decisions: traveling first class is comfortable and sending a package overnight is convenient, but either costs considerably more than the standard service alternatives. These can be difficult decisions, which means that service can be as important as efficiency.

In this context, however, service seems likely to be overshadowed by other issues. Efficiency is dominant in air transportation. Commercial air carriers have repeatedly refused to offer better service (better amenities, more seat room, clear and timely information) to economy-class passengers, insisting that they are unwilling to pay for it.<sup>33</sup> Similarly, space transportation systems are mainly evaluated by cost per pound to orbit (a type of efficiency) and reliability (an aspect of safety and cost-efficiency); service considerations usually pale in comparison. The importance of safety has already been discussed. All things considered, therefore, service is unlikely to be a prominent factor in this decision.

Note: delays may appear to be a service issue that could affect this decision, and they are important, but their main impacts relate to efficiency. There is general concern that airlines seem to ignore delays inconveniencing their passengers, but loudly protest delays affecting their operations. This is one reason Congress may begin regulating airline service.<sup>34</sup>

## Issue Synopsis

To summarize the conclusions above, efficiency appears to be most central to resolving the main decision; safety is a sine qua non that could potentially thwart change but is otherwise unlikely to differentiate options; and equity and service are generally secondary. Note that all four issues are considered again in the final policy analysis (Chapter 5), but at the outset it appears that efficiency information is most valuable for this analysis.

### **2.3.3 Required Information**

To assess the efficiency of various policy options, information is required about the disruption associated with each option under different conditions. One source of information is empirical observation. If it is possible to calculate the disruption that arose in recent cases, the severity of the problem can be assessed and some factors influencing disruption can be investigated. However, the information this can provide is limited to cases that have actually



occurred. Being prospective, this research is especially concerned with conditions that may develop in the future. In order to explore new and different possibilities, a model is required. It could be empirical or analytical, as long as its inputs include the policy options and scenarios of interest and its outputs include at least one reasonable measure of disruption. One approach is developed below.

Consider a single space transportation event. As explained previously, restricting SUA can be expected to cause conflicts with air traffic. A flight with a conflict cannot continue along its planned route, because this leads into airspace that is restricted (or will become so while the aircraft is therein). The two fundamental options for resolving this conflict are to hold the flight until the airspace along its route will be available, or to re-route the flight around the SUA. For this situation it is probable that all flights will simply be re-routed around the SUA, for several reasons. A flight already under way must bear direct costs (fuel, crew time, etc.) whether heading toward its destination or circling in a holding pattern, so progress is preferred. Flying at 450 knots, the worst conceivable case for circumventing the Eastern Range SUA should take only about 25 minutes of flight perpendicular to the intended route to pass by the SUA's near side, and then 25 minutes back on the far side. That is flying most of the way around; geometry indicates that an average deviation should involve a total extension under 15 minutes. Weighing a delay that is probably under 15 minutes (at most 50) against holding for an uncertain interval (possibly hours) until the airspace reopens, it is likely that nearly all flights already en-route will simply be re-routed and continue.

Flights that have not yet taken off must be considered separately, since the FAA prefers to hold flights on the ground rather than in the air whenever possible, for safety and efficiency. Like many aspects of ATM policy, however, this practice is primarily designed to resolve network congestion. Major airlines structure their routes using hub-and-spoke networks so they can offer more frequent (albeit indirect) service to more destinations through a series of connections at their hubs. When there is congestion at a hub, however, not only are directly affected flights delayed, but connecting flights may not be able to arrive or depart on time, causing network effects that can ripple throughout the air traffic system. Importantly, however, SUA is purely an en-route factor; it never affects the arrival or departure rates at terminals. (There are two major respects in which SUA impacts differ from those of storms that restrict airspace availability: storms move, sometimes over major hubs, and storms are much less predictable than SUA.) Since active SUA does not affect options for landing when flights reach their destinations, there is no reason to prevent them taking off. Further, there is a good reason to encourage it – while waiting, those planes can affect other ground operations (at gates, on taxiways, etc.) and exacerbate delays. Therefore it is doubly logical for the SUA conflicted flights to take off on time, and simply re-route from the beginning. Interestingly, this has the added benefit of minimizing the total deviation, though that is not a

factor in the decision to hold a flight or clear it for takeoff. (To see why deviation is affected, consider traveling along two sides of a rectangle vs. along the diagonal. If a flight must circumvent an area, this diagonal advantage arises twice: earlier deviation on the near side and postponed return to the original path on the far side each reduce flight length.)

### Direct Effects

From the above, it is reasonable to expect that almost all flights with SUA conflicts do proceed (as opposed to being held) and are simply re-routed. The required information, however, is how much disruption this causes. This must be analyzed in terms of both *direct* and *indirect* effects. Direct effects are the impacts on the specific flights that actually conflict with the SUA and therefore have to adjust their flight plans. As explained, those flights are re-routed around the restricted airspace, so the direct disruption effects are the delays this causes. SUA geometry and typical airliner cruising speeds suggest that these delays are small, but it is necessary to investigate how many flights experience delays of what extents to evaluate the aggregate problem. Unfortunately, this turns out to be easier said than done.

The major complication is the lack of a standard procedure for conflict resolution. Federal Aviation Regulations simply prohibit unrelated flights from entering the SUA while it is active, and the details of compliance are left up to the pilots or controllers. Therefore some flights are re-routed shortly after the conflicts are discovered, others fly close to the SUA before deviating in hopes the airspace will become available, and the rest can do anything in between. (Some of this variation is visible in Figure 1.2.) The level of conservatism also varies, with some flights skirting the edge of the SUA while others avoid it by a wide margin, but this makes a smaller difference than the timing of the conflict resolution decision. Basically, the unpredictable nature of such integral factors makes it impossible to develop a specific and accurate disruption model, whether analytical or empirical.

It turns out to be similarly difficult to investigate actual historical disruption. It may appear as simple as subtracting the planned flight times (gate-to-gate) from the actual times, and this would suffice if these data were precise. But as anyone who has flown has probably experienced, almost every phase of flight is subject to stochastic variation influenced by numerous factors. Airlines know this, so they build buffers (usually of about 15 minutes) into their schedules. Thus even when small delays are experienced, they rarely appear. A solution might be to compare the airborne block times alone, but this uncovers the true impediment to comparing flight times to analyze delays: finding cases that can be defended as comparable. Even between occurrences of the same "flight" (the regular service offered by one airline between the same cities at the same days/times) the actual route and speed are heavily affected by various atmospheric conditions, notably winds, which are highly variable over

time. Different aircraft also may be rotated in and out of service, and even if it is the same vehicle it may not be bearing similar loads on different trips. These factors can confound individual flight comparisons so greatly that it is rarely attempted. Instead, most comparisons focus on average values derived from large data sets. However, SUA events have occurred too infrequently to generate sufficient data for such this approach.

In light of the above, assessing direct disruption effects with precision seems infeasible, but other relevant information can still be obtained. Abstracting slightly, the analytical focus can be shifted from disruption itself to the principal factor driving it: the number of conflicts. The re-routing decisions for resolving specific conflicts and their direct consequences may be variable, but identifying which flights must take some action – i.e., those with conflicts – is straightforward. This is valuable information. Even if nothing else about re-routing the conflicted flights could be known, the conflict counts for different events would provide a basis of comparison: to first order, more or fewer conflicts represent commensurately more or less disruption. Given the degree of uncertainty associated with the effects of current events and various aspects of future developments, conflicts may be the most reliable general metric of disruption, indicative of both direct and indirect effects.

More information is available, however, so the direct disruption associated with conflicts can be refined. Specifically, the SUA geometry is fixed and known. This is the physical standard that actually imposes disruption; in general, the larger the restricted area, the further out of their way flights must deviate to avoid it, regardless of their specific conflict resolution decisions. Combined with information about the distribution of air traffic in the vicinity, this enables assessment of the average disruption per conflict.

In theory, the average number of conflicts caused by an SUA event multiplied by the average disruption per conflict should provide a reasonable estimate of the average disruption per event – the total delay minutes associated with re-routing to resolve all direct SUA conflicts, as determined by analysis of the local air traffic and the restricted airspace. Before examining this possibility in more detail, indirect effects are considered below.

### Indirect Effects

Aside from direct disruption, there may be various indirect effects. These include any air traffic disruption that arises as a result of SUA activation, but affects flights that do not have direct conflicts with the SUA. The two principal sources of indirect disruption to consider in this case are secondary conflicts and network effects.

A secondary conflict is caused when the resolution of one conflict, called a primary conflict, induces a new conflict that would not have occurred if not for the actions taken to resolve the

primary conflict. (It may sound counterproductive to resolve one conflict in a way that causes more, but this can occur if the secondary conflicts are less immediate, if they requires less deviation, or if they are simply not anticipated.) Here, SUA activation is the initiating event that causes primary conflicts, and as aircraft deviate to resolve those (by circumventing the SUA), any conflicts with other flights (otherwise not affected by the SUA) are secondary conflicts. It has been shown that secondary conflicts can become significant, with effects approaching and possibly even outweighing the direct disruption, in situations of high traffic density and constrained airspace.<sup>35</sup> As one would expect, however, the disruption associated with secondary conflicts decreases rapidly as traffic density declines or airspace in which to maneuver becomes available. This combination makes secondary conflict disruption a highly nonlinear phenomenon; under normal and low traffic density conditions it is negligible, but if traffic builds up in a constrained area it can quickly become significant.

However, these qualities suggest that the disruption associated with secondary conflicts is insignificant compared with direct effects in this case. Current space-related SUA is defined predominantly offshore, with only slight overlap of coastal launch ranges. Air traffic density, however, falls off rapidly with distance offshore, as will be shown in section 3.4. (This is because most traffic is still routed along airways, and these were originally defined between waypoints with navigational beacons, which naturally had to be on land.) As there is not much traffic routed offshore, secondary conflicts would ordinarily be of little concern. But restricting airspace causes traffic compression beside the SUA, increasing traffic density, and as a result more conflicts do occur. In these cases, however, the other condition is not met; the airspace in which to maneuver is not constrained. Over land there are not other nearby restricted areas or major airports, and offshore is just open ocean. Finally, resolving secondary conflicts involves avoiding individual aircraft (by at least 5 NM), which requires much less deviation than circumventing SUA. In short, the disruption associated with secondary conflicts around SUA events is not expected to be significant.

The other type of indirect disruption mentioned above was network effects. The most serious of all forms of disruption, network effects occur when any disruptions begin interfering with connections, which then propagate disruption throughout the air traffic system. The worst example is when a storm hits a major airport. Both arrivals and departures are greatly reduced, if not completely shut down for a while. Flights that do get through are delayed, but many flights are canceled, and others end up being diverted to airports other than their planned destinations. These three forms of disruption are increasingly undesirable, so given any opportunity, airlines take steps to avoid cancellations and especially diversions. But network effects routinely cause all three kinds of disruption, often at great distances from the initiating events. If the airport is a hub, the effects can be enormously widespread.

Moreover, the initiating events need not be extreme to induce network effects. After a point, simple airborne delays begin to affect connections; some may even force cancellations (but diversions are caused only by terminal problems). As delays grow longer, the disruption grows nonlinearly, for two reasons. The first is connectivity – the very reason networks are valuable, working in reverse: the more flights are delayed, the more connections can be disrupted. This alone can escalate rapidly if a hub is affected. The second factor is that crews begin to approach the end of their duty cycles. This forces the airlines to fly them home and send in replacement crews for subsequent operations. Together, these effects can amount to greater disruption than the direct event would appear to warrant, although much less than the nationwide impacts of the worst case, above.

Fortunately, however, network effects turn out not to be a concern in this case. First of all, SUA is static and does not encompass any terminals, it affects en-route operations only. No hubs are directly affected and no diversions are caused, so the most severe network effects are immediately ruled out. This would still leave the possibility of delays alone resulting in significant disruption as just described, except that the delays do not get large enough. As mentioned earlier, considering a cruising speed of 450 knots and the fixed SUA geometry, it appears that the average delay should be less than 15 minutes. This is simply not sufficient to induce network effects. In fact, because of the extra time built into airline schedules to reduce the effects of stochastic variation – and around SUA they might increase this buffer slightly – this would almost never result in flights appearing to be delayed at all.

A 1997 MITRE study of the actual impacts of the effects of a launch from the Kennedy Space Center on air traffic supports this reasoning. The first two points below are similar analyses of the problem; the third is a part of the findings:<sup>1</sup>

- “The [FAA] defines a delayed flight as one that is delayed at least 15 minutes... By this definition, very few flights are delayed by a space launch.”
- “Truly large, cascading disruption costs from cancellations and diversions are assumed not to occur with a commercial space launch. Launches tend to be predictable, and alternative routes exist, so delay is assumed to be bounded by approximately an hour.”
- “During the airspace restriction... The average delay per flight was estimated to be 10.1 minutes. [A preliminary] study estimated 9.6 minutes; these numbers are consistent to the accuracy of the data.”

In summary, indirect disruption, in the form of either secondary conflicts or network effects, is not expected to be significant for the case of SUA. Therefore, the direct disruption alone is deemed a reasonable first order representation of the total disruption per SUA event, appropriate for high-level policy analysis.

## Total Annual Disruption Cost

As explained above, information about traffic routing decisions and their actual impacts is so limited that the best focus appears to be conflicts as the fundamental indicator of disruption. The value of this indicator can be improved by simultaneous consideration of SUA conflict geometry to estimate the direct disruption (delays associated with circumventing the SUA) per conflict. If the average number of conflicts per SUA event ( $N$ ) and the average disruption per conflict ( $D$ ) can be determined, their product should provide a reasonable estimate of the total disruption, in delay minutes, associated with an average SUA event. (The validity of using average values for these and subsequent factors will be examined shortly; it is just held until after this line of reasoning for clarity.)

But there are many SUA events every year, which should be taken into account as it seems unlikely that the best policy for fewer than 10 space transportation operations per year would be the same as that for more than 100.\* Indeed, space operations are half of the matter. The primary motivation for this research was that RLVs might facilitate considerably more frequent space operations, and that this might be better handled by an alternative aerospace traffic management policy.

Accordingly, instead of the total disruption per SUA event, the focus should be total annual disruption. Rigorous calculation of total annual disruption would require analysis of the air traffic disruption, as described above, for each event in turn. But for scenarios involving many events, and especially for analysis of an extended period, this would be laborious. To save effort and facilitate rapid analysis, a reasonable approximation is to multiply the average number of conflicts per SUA event ( $N$ ) by the average number of events per year ( $E$ ), yielding an estimate of the average number of conflicts per year, and to multiply this by the average disruption per conflict ( $D$ ) to calculate the total annual disruption.

This information should be of significant value for assessing the total annual disruption under various policy options and investigating the sensitivity of these quantities to changes in key parameters, such as air traffic levels. This is exactly the sort of investigation required for this policy analysis, yet a final consideration remains: the units of total annual delay minutes are not of easily recognizable significance, except perhaps to air traffic experts. To facilitate general interpretation of the findings, it is desirable to present them as a cost in dollars. Fortunately, this is possible, since all of the units being aggregated are en-route delays, which are often evaluated as costs. Accordingly, the total annual disruption can be multiplied by the cost per unit disruption ( $C$ ) to approximate the total disruption cost per conflict.

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\* The last five years have averaged 32 launches and 6 Shuttle landings per year.<sup>15, 16</sup> Including all of the delays/rescheduling (not centrally recorded), it has probably resulted in at least 50 SUA events annually.

Thus inductive reasoning has led to a simple equation for the total annual disruption cost ( $J$ ):

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

where  $N$  represents the average number of conflicts per SUA activation event,  $E$  represents the average number of space transportation SUA events per year,  $D$  represents the average amount of disruption (direct delay minutes) per conflict, and  $C$  represents the average cost per unit of disruption (dollars per minute of en-route flight extension).

### The Use of Average Values

Two concerns may arise from the use of average values as described above. The first relates to the significance of the average values themselves. A statistical average is merely the sum of all observed values divided by the number of observations. This statistic is notable because it is the expected value of future observations. Alone, however, an average does not provide information about the distribution of events. For example, an average arrival delay of 10 minutes for three flights could describe various circumstances: all three flights 10 minutes late, one on time and the others each 15 minutes late, one 5 minutes early and the others 10 and 25 minutes late, etc. Therefore it is of value to also examine the actual distribution where possible. Of particular concern is the possibility of a long “tail” on the distribution, which would indicate a very low probability event. This is of interest because being low probability, it would not significantly affect the average, but if it is high severity it could still be of import for the policy decision. Examples of policies addressing just such events abound in safety precautions – against a dam collapsing or a nuclear power plant meltdown, etc. Since SUA is also a safety measure, this is a potential concern.

Unfortunately, the actual distributions of SUA conflicts ( $N$ ), disruption ( $D$ ), and events ( $E$ ) are unknown. As explained previously, there are no readily available data describing which flights had SUA conflicts or how they were disrupted. Comparison of individual flights in the vicinity of SUA while it is active and inactive can be attempted, but the results are confounded by changing conditions. The actual distribution of SUA events ( $E$ ) is either not recorded or not a matter of public record. However, the numbers of launches and landings are known, and were presented in Chapter 1. These are the major drivers of  $E$ ; the only unknown effects are extended or rescheduled SUA events for individual operations.

This said, the underlying concern can nevertheless be assuaged: there are no low probability, high severity events masked by the average values that should be considered in this policy decision. Conflicts ( $N$ ) are estimated using traffic density, the variations in which are examined in Chapter 3. The forces driving traffic density, i.e., airline scheduling, are well understood, and there is no possibility of suddenly getting much more traffic than expected.

The average disruption (**D**) is even simpler, based on the size of the SUA. Since this does not change there is currently no variation other than pilot/controller choice about precisely how to re-route, and this variation is both small and bounded by rational behavior – no flight will deviate by much more than the minimum needed to avoid the restricted airspace. There are no plans to change SUA size except possibly to make it smaller, which acts in the opposite direction of the unlikely event concern. Finally, it is potentially conceivable that SUA events (**E**) could briefly surge in the event of a true emergency, such as space warfare. But in the face of such an emergency, traffic disruption would be trivial, and it is fairly likely there would be only emergency air traffic flying anyway.

Consequently, even though the distributions surrounding these factors are not known, there is reason to have confidence in the predicted average values, at least as first approximations (recall that no information has been previously available about many of these effects), and perhaps more importantly, no reason to fear that critical but low probability events are being omitted.

The second concern about the validity of using average values as in Equation 1 relates to multiplying them without addressing interaction effects. For any group of parameters, it is only necessarily true that the product of the averages is equal to the average of the products if they are independent; otherwise, there may be interaction effects. In fact, it is not asserted that the four factors in Equation 1 – conflicts per event (**N**), SUA events per year (**E**), deviation per conflict (**D**), and cost per unit deviation (**C**) – are independent in general. **E** and **C** are truly independent and unrelated to the other factors, but **N** and **D** can have a connection through traffic density.

However, **N** and **D** are independent as calculated in this analysis. The reason for this is that **D** is only being calculated in terms of the minimum required to avoid the SUA. Interaction effects between **N** and **D** arise through secondary conflicts, if aircraft must deviate around the SUA and one-another. But as explained previously, the offshore situation of current SUA precludes significant secondary conflict effects (low offshore traffic density and sufficient airspace to maneuver). Therefore the interaction between **N** and **D** is not significant in this analysis, and using the product of the average values as constructed in Equation 1 is valid.

### Discussion of Equation 1

Equation 1 is a simple approximation of the total annual disruption cost (**J**) based on the average values of four factors. (These *average values* are also referred to as *expected values* when predicting future behavior.) Of course, such an assessment based on aggregate averages is unlikely to be precise. There may be notable behavior, such as a class of conflicts



involving disproportionate disruption, which cannot be observed when dealing only with averages. Nevertheless  $J$  can still be of value, especially for order-of-magnitude and sensitivity comparisons. Furthermore, knowledge of subtle factors contributing to  $J$  can lead to new options for mitigating this cost.

In short, Equation 1 summarizes the required information. To assess the efficiency of a given policy option, the expected values of each of the underlying factors ( $N$ ,  $E$ ,  $D$ , and  $C$ ) should be investigated. Unfortunately, these values can vary significantly with future developments (e.g., air traffic levels), and it would be impractical to analyze all potential combinations. In such cases, one approach is to identify a small number of exploratory scenarios, which are individually plausible and collectively span most of the interesting regions of the decision space. The study can focus on this manageable subset, which, although not comprehensive, can reveal options that are desirable (robust against uncertainty) or that should be avoided.

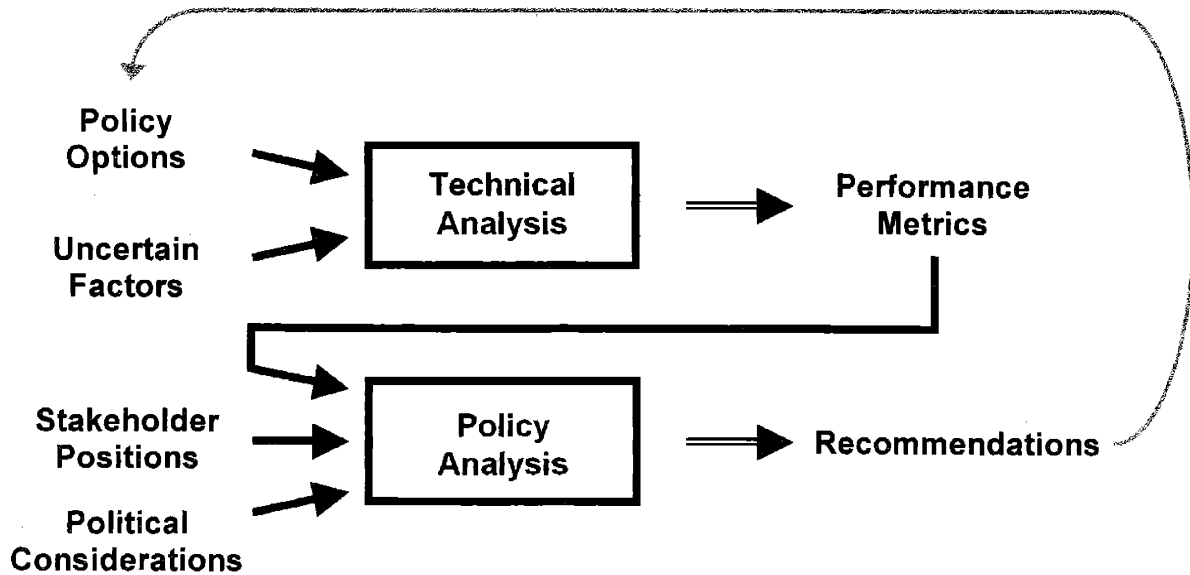
Before proceeding, it should be observed that  $N$ ,  $E$ ,  $D$ , and  $C$  are not all equally important. While the first three are fundamental contributors to the total cost,  $C$  is little more than a units-conversion factor – the concept of  $D$  developed above necessitates that the lower the total annual disruption (total delay minutes), the lower the total annual disruption cost. For this study, the value used for  $C$  is a recent estimate for commercial airlines of \$62.50 per minute of airborne delay.<sup>36</sup> It is possible to model  $C$  in greater detail, of course, but this would be of relatively little help in resolving the high level policy decision. As a result, only  $N$ ,  $E$ , and  $D$  are examined in detail in the technical analysis.

Finally, note that this construction of  $J$  is based on a policy under which air traffic normally has access to the airspace, but SUA activation transfers full priority to space operations. This assumption that space operations can disrupt air, but not vice versa, actually frames  $J$  as the cost of disrupting air traffic alone. But this is not necessarily inequitable: the total cost can be framed in this way for analytical convenience; the policy option that minimizes  $J$  can be identified; and what cannot be reduced further can be fairly distributed between air and space users. This would be beneficial – substantially better than continued ignorance of both the magnitude and distribution of the cost. But it should be recognized that there is no guarantee that minimizing  $J$  will result in the globally minimum disruption cost.

### ***2.3.4 Analytical Structure***

The final step is to develop an analytical approach – a feasible combination of engineering and policy studies anticipated to best facilitate resolving the main decision. For this study, it was decided to organize the research into two phases, referred to as the *technical analysis* and the *policy analysis*. The goal of the first phase is to gather appropriate technical

information; the goal of the second phase is to combine that information with relevant policy factors to analyze the decision. Figure 2.2 illustrates this framework graphically. In many policy analyses the process is iterative, as the findings of one loop lead to a better formulation of the problem for the next.



**Figure 2.2 Two-Phase Framework for Integrated Engineering/Policy Analysis**

The primary inputs to the technical analysis are the *policy options*. Here, these consist of options for separating air and space traffic strategically (via SUA of various parameters) and tactically (via various conflict detection and resolution procedures). The other inputs are *uncertain factors*, so named not because they cannot be identified, but because their values cannot be specified in advance. Examples include future air traffic levels, ATM procedures, and RLV technologies. All of this information can be modeled to determine various *performance metrics* associated with each set of options. These metrics are quantitative representations of various values.

The metrics then become inputs to the policy analysis, in which they are analyzed along with *stakeholder preferences* and various other *political considerations*, such as issue importance, consensus, and opposition. The end results are *recommendations* about the policy options expected to perform best under various circumstances.

This concludes the overview of the analytical approach developed for this study. The next chapter focuses on the Airspace Conflict Model developed to analyze  $N$ , and the following chapters present the actual technical and policy analyses, including detailed descriptions of each of the components shown in Figure 2.2.



## Chapter 3: Airspace Conflict Model

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This chapter focuses on the significance, derivation, and validation of the analytical model developed to predict the number of conflicts associated with restricting airspace.

### 3.1 Significance of Conflicts

In Chapter 2, the total annual disruption cost ( $J$ ) associated with the air traffic management (ATM) policy of using Special Use Airspace (SUA) for strategic air and space traffic separation was presented as the product of four factors (Eq. 1):

- $N$  – the average number of air/space traffic conflicts per SUA event
- $E$  – the average number of space transportation SUA events per year
- $D$  – the average disruption (direct airborne delay minutes) per conflict
- $C$  – the average cost per unit disruption (\$62.50 per minute airborne delay)

In short, the reasoning was that  $E$  SUA events occur per year, each of which causes an average of  $N$  air traffic conflicts, where each conflict induces  $D$  delay minutes of disruption, which are finally converted via  $C$  into an estimate of the total annual disruption cost  $J$ .

Of these,  $N$  is the most important for this analysis of the total cost,  $J$ . Regardless of the details of the conflicts and the procedures used to resolve them (both of which influence  $D$ ) or the specific values of the other factors, it is a valid first approximation that the fewer the conflicts, the lower the total disruption cost. Accordingly,  $N$  can be considered the fundamental factor of  $J$ , most important for resolving the policy decision.  $N$  is also the most controllable, since the restricted airspace volume ( $S$ ) and active duration ( $T$ ) are directly set as a policy decision. Finally,  $N$  is the least situation-dependent of the four factors, and therefore the most useful for generalization. For all of these reasons, it was deemed essential to this study to develop a reliable means to model and predict it.

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, but results are needed for a known situation. If the relationships between the system elements are sufficiently well-understood to be represented mathematically, however, an analytical model may be constructed. This can be used to predict aspects of system behavior from a more global or general perspective.

A number of powerful empirical models have previously been developed for airspace and air traffic problems. Examples such as the Total Airport and Airspace Modeler (TAAM), Collaborative Routing and Coordination Tools (CRCT), and the Future ATM Concepts Evaluation Tool (FACET) are recognized as excellent for various modeling capabilities. TAAM, created by Boeing's Preston Aviation Solutions, is a sophisticated fast-time simulation model of air and ground operations. Excellent for deterministic analyses, it is able to model almost any level of detail the users wish to program into their scenarios.<sup>37</sup> CRCT was developed by MITRE's Center for Advanced Aviation System Development as a real-time aid to controllers, predicting conflicts and facilitating "what-if" investigation of re-routing options around flow-constrained areas without overloading nearby sectors. It can also be used for fast-time "playback" or as a diagnostic tool.<sup>38</sup> Finally, FACET was developed by NASA Ames as a simulation platform to facilitate the development and analysis of advanced air traffic management (ATM) concepts. It features four-dimensional trajectory modeling of en-route operations, with customizable conflict detection and resolution rules, and also models weather and airspace features.<sup>39</sup>

Such tools are extremely capable for the problems they were designed to investigate. However, every model involves a tradeoff between flexibility and fidelity, and this study simply called for more flexibility than empirical models could readily accommodate. Among the potential developments of interest in this study are new SUA parameters (size, location, active duration), various air traffic scenarios (density, route structure, aircraft mix), and a number of proposed space transportation operations (vertical/horizontal launch/landing, supersonic/subsonic cruise, etc.). It is likely that each of the models above could theoretically handle many of these options, but only with intensive effort to program each scenario, such that only a few could be investigated in one study. It was most important for this research that the model of choice facilitate rapid investigation across this broad decision space, so the factors affecting the policy decision could quickly be determined. In short, despite the power of some empirical models, a more flexible solution was sought.

Moreover, no analytical models of airspace/traffic impact have been available. A few gas models have been created representing aircraft as particles with various distributions, but these have been primarily used to investigate probabilistic conflict rates. Various extensions model flows and directionality in different spaces, but none of these have addressed conflicts with a region of airspace. Consequently, a new analytical model was derived to facilitate these types of conflict studies. This is introduced below.

## 3.2 Derivation

To develop a general representation of airspace conflicts, consider that restricting a region of airspace to air traffic for a period of time can cause conflicts by two distinct mechanisms in time and space: *displacement* of aircraft within the airspace at the moment of activation, and *encounter* by aircraft initially outside the airspace, but planning to enter it before the moment of deactivation. This distinction can facilitate analysis, because the displacement and encounter conflict mechanisms are independent. Therefore, they can be analyzed separately and then combined to determine the total number of conflicts for a given scenario:

$$N = N_{disp} + N_{enc} \quad (2)$$

### 3.2.1 Displacement Conflicts

The average or expected number of displacement conflicts ( $N_{disp}$ ) is simply the number of flights within the restricted airspace at the moment of activation. This can be calculated from two factors: the volume of restricted airspace ( $S$ ) and the average background air traffic density ( $\rho$ ):

$$N_{disp} = S \cdot \rho \quad (3)$$

Here, traffic density is defined as the number of aircraft per unit volume (or area for 2-D analyses) of airspace – the classical physics concept of density. It should not be confused with *dynamic density*, a measure of traffic complexity. Average traffic density values for longer intervals are also valid, assuming fluctuations are generally small.

### 3.2.2 Encounter Conflicts

Modeling the number of encounter conflicts is slightly more complicated, involving three factors. In order to explain those, however, it is first necessary to introduce the concept of *reference airspace*, a region analyzed to determine the background traffic density ( $\rho$ ). This is required because air traffic flows are nonuniform. Aircraft take off and land as permitted by circumstances at terminals; cruise at altitudes and velocities appropriate for the aircraft type, weather conditions, and traffic situations; and are routed for a combination of safety, efficiency, equity, and service (convenience and comfort). As a result, any snapshot of a (reasonably large) region of airspace is likely to include a combination of orderly streams and random particles, all of which contribute to traffic density. The reference airspace is simply the region selected for this measurement.

The size, shape, and location of the reference airspace are arbitrary; the only constraint is that it must include the entire SUA (i.e., all of the airspace that may be restricted in the study). If the reference airspace is larger than the SUA, a potential drawback is that traffic density variation within the area could reduce the precision of conflict estimates based on the average traffic density. Nevertheless this may be practical, for example if an appropriate area – such as an air traffic control sector – has already been defined for other purposes, and data for this area is readily available.

Encounter conflicts can be defined using three factors: the traffic obstruction ( $\phi$ ), or percentage of traffic entering the reference airspace that encounters the SUA; the arrival rate ( $\lambda$ ), or number of aircraft entering the reference airspace per unit time; and the active duration ( $T$ ), or length of time for which the SUA is restricted. The number of encounter conflicts is then the product of these three factors:

$$N_{enc} = \phi \cdot \lambda \cdot T \quad (4a)$$

Actual air traffic in controlled airspace is typically organized into a number of discrete flows along airways. Consequently, if a given traffic pattern is composed of a number of separate flows, then encounter conflicts could be calculated for each flow  $i$ , and all of these combined would determine the total encounter conflicts for all traffic in the airspace. This gives rise to the discrete form of the equation for encounter conflicts:

$$N_{enc} = \sum_i (\phi_i \cdot \lambda_i \cdot T) = T \cdot \sum_i (\phi_i \cdot \lambda_i) \quad (4b)$$

With the trend toward free flight, however, air traffic may not always be organized in flows. For this case, or any other in which average values describing the overall traffic pattern are more convenient than summing individual flows, the average obstruction and arrival rate can be used in Equation 4a to calculate the average number of encounter conflicts.

### 3.2.3 Total Conflicts

As noted earlier, the equations describing displacement and encounter conflicts can be simply combined to represent total conflicts. Any forms of the component equations can be used. Shown below is the average-form equation for total conflicts ( $N$ ):

$$N = S \cdot \rho + \phi \cdot \lambda \cdot T \quad (5)$$

Equation 5 is a general analytical model of the conflicts caused by restricting airspace, as a function of five parameters. It is already useful, but it can be further simplified through two assumptions of idealized traffic behavior:

- traffic density is constant in the reference airspace
- traffic entering the reference airspace is uniformly distributed in space

Of course, actual traffic is unlikely to be ideal; specific flows, averaged over the long term, will frequently fail to support these assumptions. Nevertheless, it is argued that they are generally suitable for properly selected areas and time frames. This is supported by the validation at the end of this chapter.

The assumption of constant traffic density in the reference airspace establishes a relationship between arrival rate and traffic density, as described by the fluid dynamics of a steady mass flow. Although air traffic may not intuitively seem to approximate a fluid very closely, the following relationship holds for any steady, incompressible flow:

$$\lambda = \rho \cdot V \cdot A \quad (6)$$

where  $V$  and  $A$  are the velocity and cross-sectional area of the flow, respectively. (Note: for this type of application, multiple discrete flows can be theoretically modeled as a single aggregate flow: each discrete flow  $i$  of specific  $V_i$  and  $A_i$  can be represented as a combination of  $x$  and  $y$  flow components, which can be added to calculate the  $x$  and  $y$  components of the aggregate flow.)

The second assumption, that traffic entering the reference airspace is uniformly distributed, leads to an equation relating  $A$  and  $\varphi$ . If the traffic entering the reference airspace is modeled as a single flow described by  $\rho$ ,  $V$ , and  $A$ , then the traffic obstruction presented by the SUA becomes the ratio of the SUA cross-sectional area ( $a$ ) to that of the flow ( $A$ ):

$$\varphi = a/A \quad (7)$$

Equations 6 and 7 enable substitution for  $\lambda$  and  $\varphi$  in Equation 5, which yields:

$$N = S \cdot \rho + a \cdot \rho \cdot V \cdot T \quad (8)$$

At this point, one last identity must be introduced: the mean transit time ( $\tau$ ), or average time it takes air traffic to fly through the airspace when it is not restricted. Logically, this is just the length of the average path through the SUA, divided by the average aircraft speed. In terms of the parameters already introduced, this can be represented as follows:

$$\tau = (S/a)/V \quad (9)$$



Using this to substitute for  $a$  and  $V$  results (after simplifying) in the general form of ...

**The Airspace Conflict Model (ACM):**

$$N = S \cdot \rho \cdot (1 + T/\tau) \quad (10)$$

This compact equation describes the average value of the total (displacement and encounter) conflicts associated with restricting airspace as a function of only four parameters:

- $S$  – the volume of the restricted airspace
- $T$  – the duration for which the airspace is restricted
- $\rho$  – the average air traffic density
- $\tau$  – the average airspace transit time

### 3.2.4 Implications

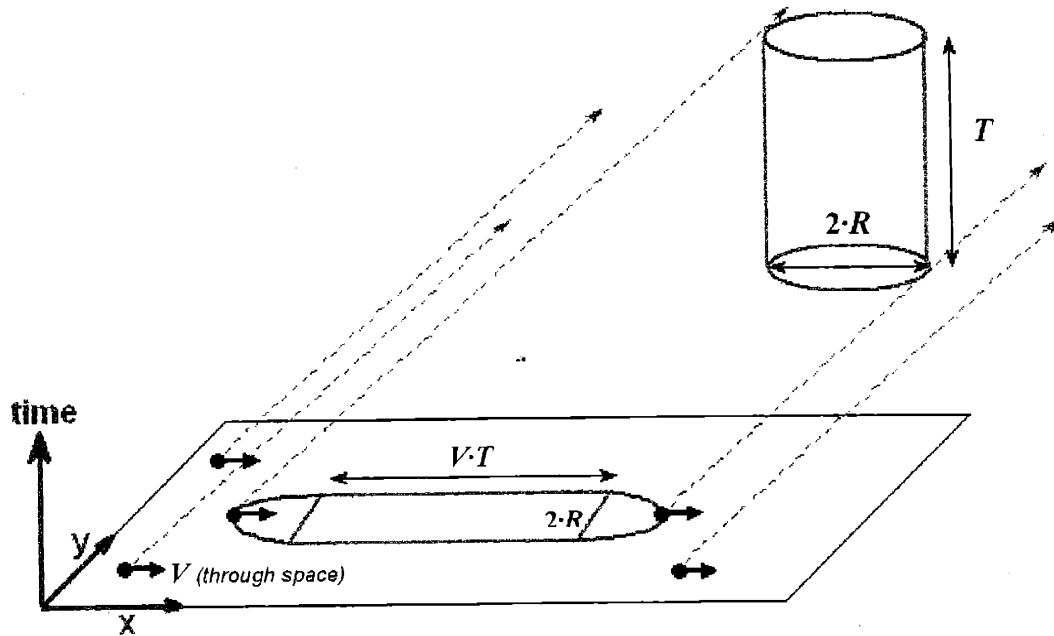
The simplicity of the general form of the ACM (Equation 10) makes it ideal for broad studies, investigating a broad range of scenarios for generally favorable conditions. For more detailed studies, each component of Equation 8 can be more precisely modeled to incorporate available information, such as a known route structure in the vicinity of the SUA.

In addition, an analytical model clarifies the relationships (several of which are examined in section 3.4) between individual factors. For example,  $N$  should increase linearly with  $\rho$ , while the relationship between  $N$  and  $S$  is more complex, because changing  $S$  may also impact  $\tau$ , depending on the geometry of the SUA and traffic flows. These relationships can even have policy implications. If  $\tau$  is large relative to  $T$ , then  $N$  should be insensitive to that duration (because  $T/\tau \ll 1$ ). This could occur with either slow traffic flow or very large SUA, and suggests 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 quite sensitive to active duration, and it may be advantageous to search for policy changes that could reduce  $T$ .

## 3.3 Illustration

In this section, the ACM is explained in terms of a simple, two-dimensional example, to more clearly illustrate how it works.

Consider a coalititude planar flow of air traffic encountering a circular SUA (radius  $R$ ) that is active for a finite duration,  $T$ . As shown in Figure 3.1, 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. Since the SUA is spatially static, it is depicted in the figure as a circular spatial area extending upwards over time while it is active, thereby carving out a cylinder in space-time.



**Figure 3.1 Example Space-Time Diagram**

A few individual aircraft are highlighted in Figure 3.1 as dots in the  $x$ - $y$  plane, with arrows indicating that they are traveling in the  $x$ -direction in space. Accordingly, they trace out the dashed, slanted paths shown in space-time. Any aircraft following paths through space-time that pierce the SUA space-time cylinder encounter the SUA while it is active. Those aircraft need to be diverted or delayed to avoid entering restricted airspace, and so are counted as conflicts. To simplify the figure, only boundary conflicts are depicted – the first and last aircraft conflicting with the SUA. However, other aircraft (not explicitly shown) could be anywhere in the  $x$ - $y$  plane, and any between those bounds would also have conflicts.

To identify conflicts, the SUA space-time cylinder can be projected onto the  $x$ - $y$  plane along the direction of the aircraft space-time trajectory vectors. The area of this projection multiplied by the mean traffic density then gives the average number of conflicting aircraft. Note that projecting the space-time volume into spatial dimensions in this way is equivalent to projecting the spatial trajectories of the aircraft into space-time as described above. In

either “space” – the 2-D spatial plane or the 3-D space-time volume – any overlap between the projected aircraft trajectories and restricted airspace indicates a conflict. The former is the preferred analytical domain, however, because spatial concepts such as traffic density are more familiar than their space-time analogues.

The parameters involved already indicate that this is what the ACM is doing. Conflicts are described as a function of the traffic density and the spatial projection of the SUA space-time cylinder, where this projection is shaped by three factors: the geometry of the SUA, the duration for which it is restricted, and the aircraft speed relative to the SUA. These are the four parameters in the ACM (geometry and speed determining  $S$  and  $\tau$ ).

If the SUA was restricted only for an instant, the cylinder in Figure 3.1 would collapse into a circle, and it would simply displace any aircraft in a circular area ( $S = \pi \cdot R^2$ ). So if the mean traffic density is  $\rho$ , the applicability of Equation 3 is readily apparent, and the number of displacement conflicts is  $\rho \cdot (\pi \cdot R^2)$ .

If the SUA stays active for any duration, however, the restricted space-time cylinder gains height, which causes the projection in space to stretch laterally. In Figure 3.1, this stretching projection is rectangular in shape, and is defined by the diameter of the circle ( $2 \cdot R$ ) on the side perpendicular to the traffic velocity, and the aircraft speed times the restricted duration ( $V \cdot T$ ) on the side parallel to the traffic velocity. This projection represents the space-time encompassing any 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  $\rho \cdot (2 \cdot R \cdot V \cdot T)$ .

As noted before, the total number of conflicts is just the sum of the displacement and encounter conflicts, so the equation just derived for total conflicts in this example becomes  $N = \rho \cdot (\pi \cdot R^2 + 2 \cdot R \cdot V \cdot T)$ .

The general form of ACM (Eq. 10) was presented as  $N = S \cdot \rho \cdot (1 + T/\tau)$ . To see how this compares with  $N = \rho \cdot (\pi \cdot R^2 + 2 \cdot R \cdot V \cdot T)$  (the equation just derived for the example), the ACM is first algebraically rearranged:  $N = \rho \cdot (S + S \cdot T/\tau)$ . As it was already noted that  $S = \pi \cdot R^2$ , it remains to show that  $S \cdot T/\tau = 2 \cdot R \cdot V \cdot T$  to demonstrate equivalence.

This is a simple matter of applying some of the equations presented earlier.  $\tau$  was described (Eq. 9) as  $(S/a)/V$ , which, since  $a$  is  $2 \cdot R$ , is equivalent to  $(\pi \cdot R)/(2 \cdot V)$ . Therefore,  $S \cdot T/\tau = 2 \cdot V \cdot S \cdot T/(\pi \cdot R)$ , and substituting for  $S$  results in  $2 \cdot R \cdot V \cdot T$ . This confirms that the

ACM is equivalent to the reasoning illustrated in this simple theoretical example. More rigorous empirical validation of the model is presented in the next section.

### **3.4 Validation**

To empirically validate the ACM, radar tracking data for actual commercial flights were analyzed for the week of March 14-21, 2001. This week was selected as representative of more or less “typical” air traffic in the National Airspace System (NAS), in that operations were neither notably disrupted nor unusually facilitated by atypical conditions.

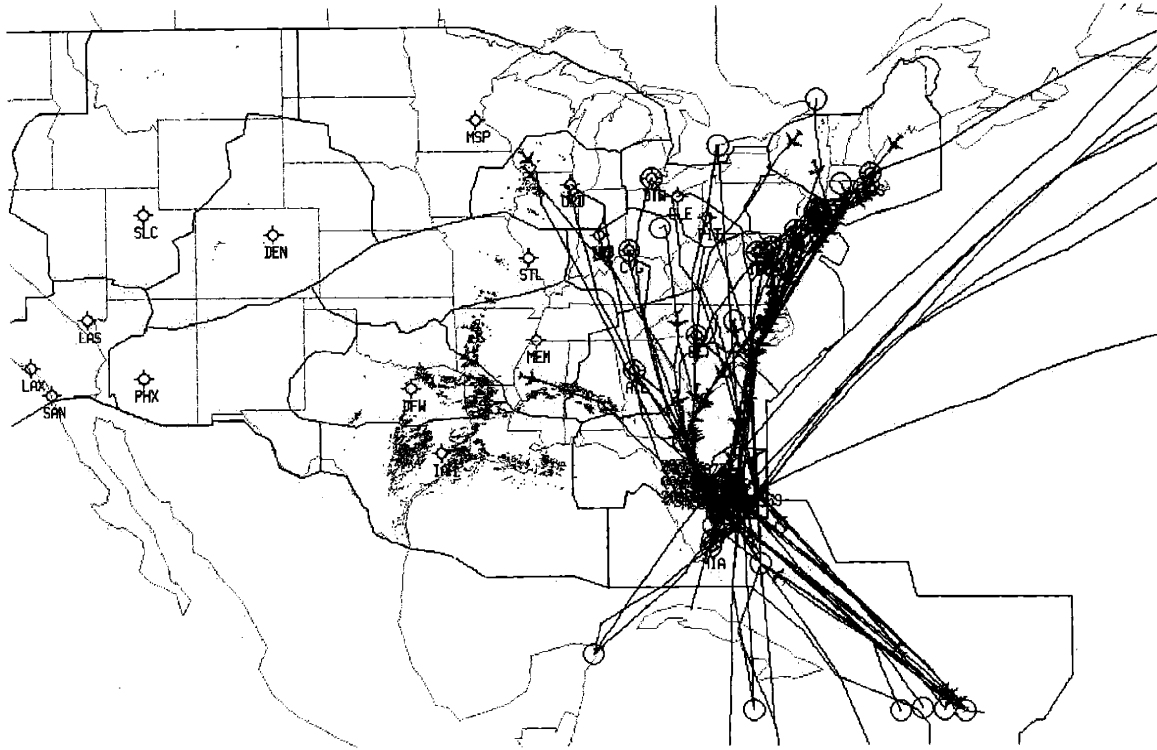
The tracking data were obtained from the Enhanced Traffic Management System (ETMS) database maintained by the Federal Aviation Administration (FAA). ETMS data contains all flight plan information filed for operations in the NAS, but only commercial flights were included for this study, because information about military flights is restricted, and general aviation (GA) flights in uncontrolled (Class G) airspace are not always reliably monitored.

The geographic area containing the SUA associated with the US Eastern Space Launch Range (depicted in Figure 1.1) was selected for analysis to validate the ACM. All altitudes from sea level to 60,000 feet are included in this SUA.

#### ***3.4.1 Collaborative Routing Coordination Tools***

The SUA was not actually restricted during the subject week, so the typical “background” traffic patterns could be examined. These were then analyzed using MITRE’s Collaborative Routing Coordination Tools (CRCT) model to compute the number of conflicts that would have occurred if the SUA had been restricted.

CRCT was designed to help air traffic controllers explore options for re-routing air traffic around Flow Constrained Areas (FCAs) – airspace with temporarily reduced traffic capacity for any reason, such as bad weather.<sup>40</sup> The user defines the spatial boundaries and restricted times for each FCA, and the software reports both current and predicted conflicts. Figures 3.2 and 3.3, respectively, are wide-area and close-up traffic displays from one of the validation studies. Only flights predicted to have conflicts if the FCA were restricted from 3:00 pm to 7:00 pm local time are shown. The aircraft icons mark the flights’ positions at 3:00 pm, and the black lines trace their full routes (as flown/planned at that time). CRCT also enables the user to experiment with re-routing options and view the predicted effects, although this capability was not utilized for the validation studies.



**Figure 3.2 Collaborative Routing Coordination Tools (CRCT) Traffic Display**

Notable in Figure 3.2 is the geographic range of flights conflicting with the SUA. In just four hours (roughly equivalent to the actual SUA restriction for many launches) flights from as far north as Minnesota and as far south as the Puerto Rico are found to be affected. Such a range is not unique or even extreme. Some transoceanic flights extend east all the way to Europe (outside the pictured region), and although it did not occur during this period, flights from the West Coast are often affected. The path extension associated with deviating around the SUA would be negligible compared to the nominal length of any flight over 1000 NM, but some – especially transoceanic flights – carefully balance their fuel and cargo loads in advance. Therefore such flights must either plan to circumvent the SUA before takeoff, and thus lose revenue by transporting fuel instead of cargo if the airspace is available, or else assume the airspace will be open and risk running low on fuel if they must circumvent the SUA.

Figure 3.3 presents a close-up view of the SUA area from the same CRCT study. A notable feature in this view is the distribution of traffic. Various routes cross different SUA sections in many directions, creating a few areas of potentially concentrated traffic, and also random “holes” where there are no flights. A static view of conflicting flight routes such as this does not reveal much about traffic density (since timing and overlap cannot be gauged), but it does illustrate that aircraft follow many paths throughout the region, resulting in complex airspace



CRCT. However,  $\rho$  and  $\tau$  were not directly controllable, since  $\rho$  is a property of the air traffic, and  $\tau$  is determined by the SUA/airway geometry and the speed of the actual air traffic. For this reason, only  $S$  and  $T$  were actively varied to construct validation scenarios.

Of course, it was still necessary to obtain values for  $\rho$  and  $\tau$ , to plug into the ACM. These can technically be determined from the raw ETMS data, but doing so with precision, especially for fairly small areas, requires CRCT or a similar model, doing fully as much computation as is required for the main conflict analysis. This leads to two options. First, if truly required,  $\rho$  can be calculated for each scenario by simultaneously (but independently) using CRCT to monitor the FCA arrival rate,  $\lambda$ , and then converting this to  $\rho$  via Equation 6. But Equation 6 requires knowledge of  $V$  and  $a$ . Of these,  $a$  is discussed below, and  $V$  can be calculated directly from the ETMS data; on average it was about 440 knots, and the variation between scenarios was too small to significantly impact predicted conflicts. However, the primary advantage of the ACM – rapid analysis without complex models – is negated if CRCT must be run to determine input values. Hence the second option as a compromise: one CRCT “calibration run” to provide  $\rho$  for one case, and use of this value for the other cases.

Finally, the values of  $a$  and  $\tau$  for each scenario were estimated on the basis of a two-dimensional, circular approximation of the SUA, with the same area as the actual SUA polygon. Neither aspect of this approximation was expected to introduce much error, since the actual SUA regions were not very irregular in shape, and practically all en-route paths through the airspace were expected to be level. Hence for each scenario, the radius ( $r$ ) of the circular approximation was simply calculated to fit the known SUA area, and then  $(2 \cdot R)$  was used for  $a$ , and  $(a/V)$  was used for  $\tau$  (2-dimensional version of Equation 9).

Below is a summary of the required parameters and the sources of each.

- $S$  – set directly (using actual SUA subsets)
- $\rho$  – calculated from Eq. 6 – requires  $\lambda$  (from a CRCT “calibration run”),  $V$  and  $a$
- $T$  – set directly
- $\tau$  – calculated from 2-D version of Eq. 9 – requires  $V$  and  $a$
- $V$  – calculated directly from actual ETMS data (same data CRCT uses)
- $a$  – estimated using 2-D circular approximation of SUA (where  $a = 2 \cdot R$ )

### 3.4.3 Varying $S$

For the first set of validation studies,  $S$  was varied by incrementally activating four subsets of the SUA associated with the US Eastern Space Launch Range:

- $S_1$ : R-2932 + R-2933 — circular approximation:  $R_1 \sim 6$  NM
- $S_2$ :  $S_1$  + R-2934 + R-2935 — circular approximation:  $R_2 \sim 18$  NM
- $S_3$ :  $S_2$  + W-497A — circular approximation:  $R_3 \sim 36$  NM
- $S_4$ :  $S_3$  + W-497B — circular approximation:  $R_4 \sim 93$  NM

In short,  $S_1$  just consists of the smallest restricted area (R-2932 and R-2933 are co-located),  $S_2$  adds the other restricted areas,  $S_3$  adds the small warning area, and  $S_4$  adds the large warning area. These restricted and warning areas are illustrated in Figure 3.4. Each of the four SUA subsets ( $S_1 - S_4$ ) was modeled as though restricted for two hours in the middle of the day, from 1200 to 1400 local time.

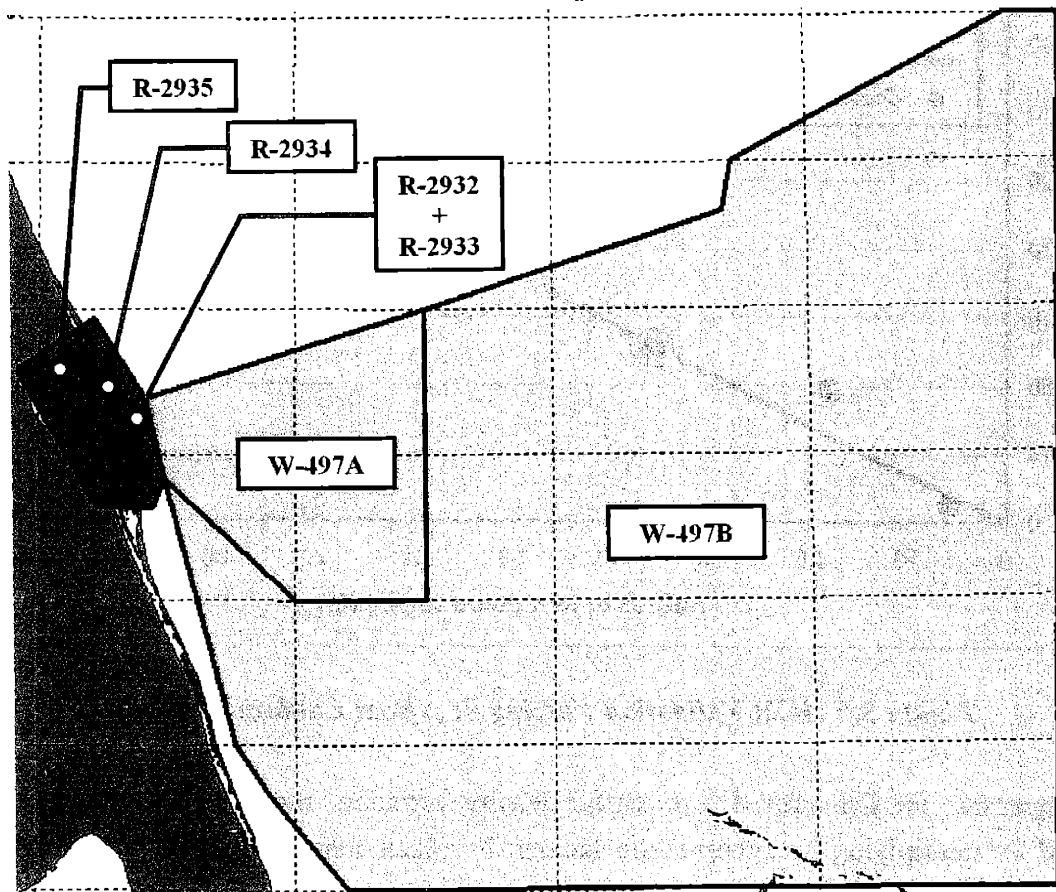
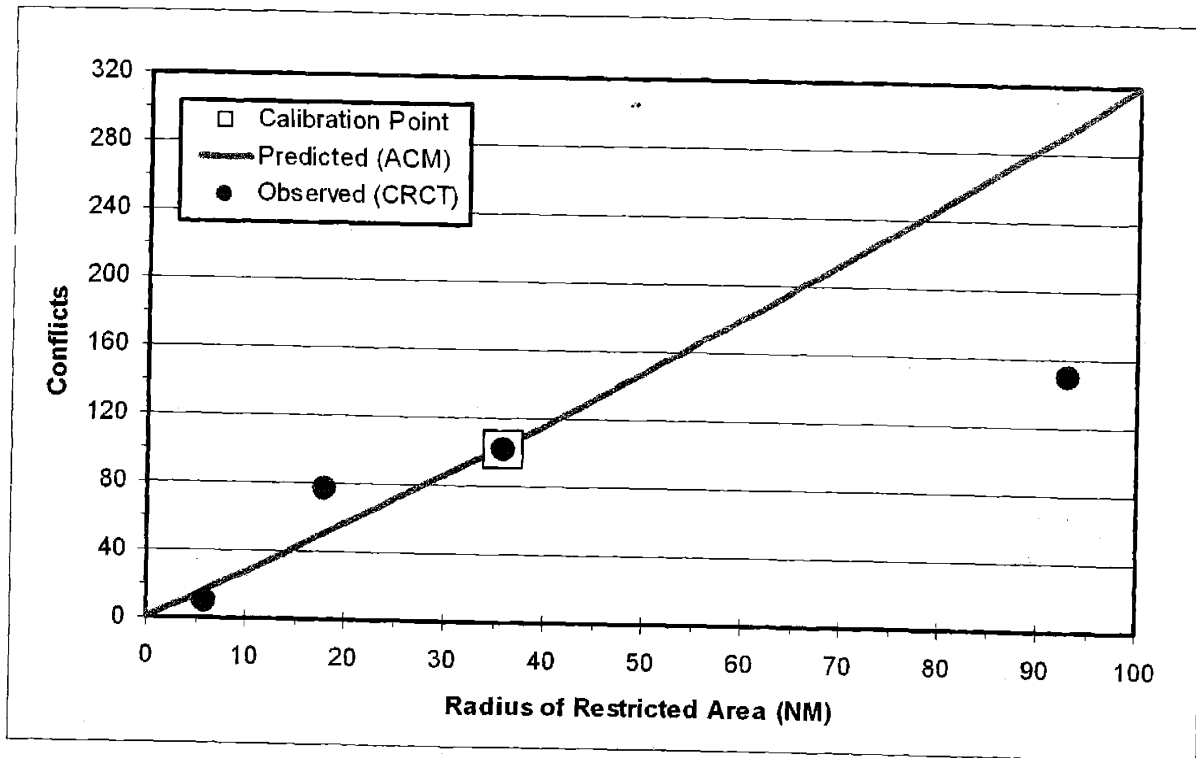


Figure 3.4 Individual Areas Within the Eastern Range Special Use Airspace (SUA)



First, a CRCT calibration run determined that the average traffic density for  $S_3$  was 15.36 aircraft per 10,000 NM<sup>2</sup>.<sup>\*</sup> This value of  $\rho$  was used in the ACM to model the other SUA sizes, predicting conflicts as shown in Figure 3.5. The predictions did correlate with the observed values ( $R^2 = 89.50\%$ ), but the fit was not sufficient to validate the ACM, being in error by nearly 100% for the largest SUA subset. However, it was unclear whether this was due to a failing of the ACM or arising from use of the  $S_3$   $\rho$  value for the other SUA subsets.

To resolve this question, the arrival rate data from CRCT were used to calculate the average traffic density for the other SUA subsets. This resulted in average traffic density values of 9.47, 24.31, and 8.52 aircraft per 10,000 NM<sup>2</sup> for  $S_1$ ,  $S_2$ , and  $S_4$ , respectively, confirming that use of the  $S_3$   $\rho$  value for the other SUA subsets was definitely a source of error.

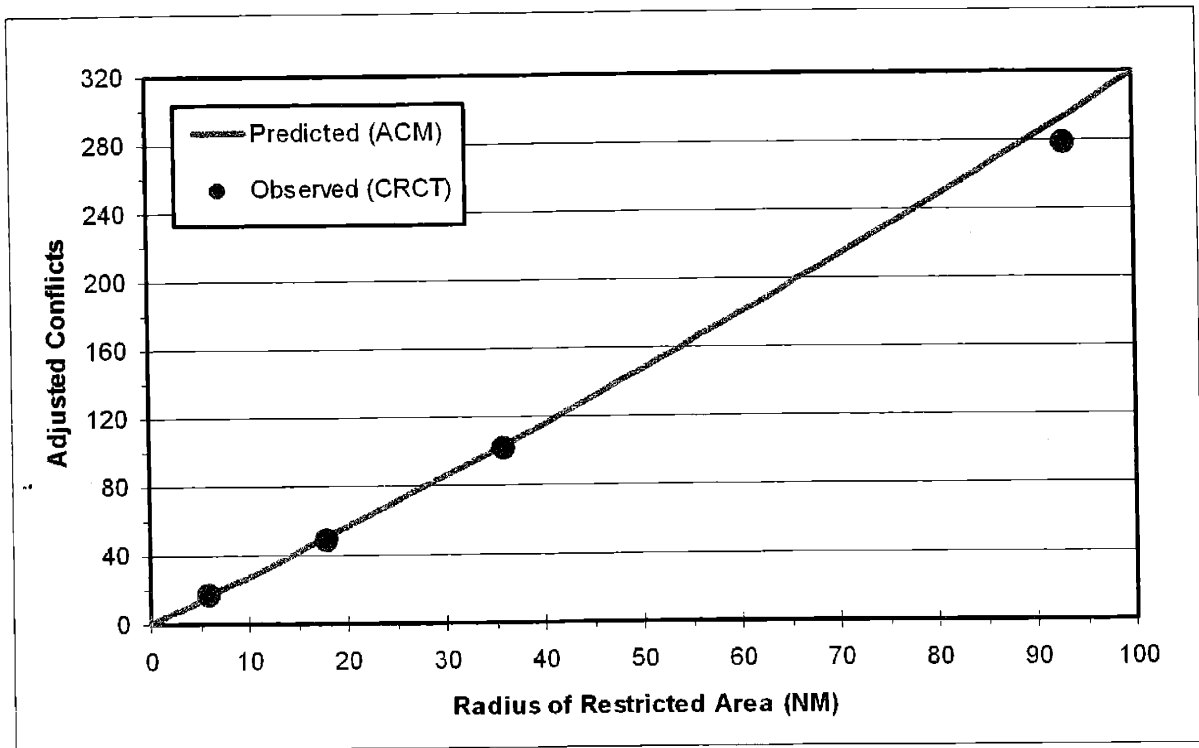


*Figure 3.5 ACM Validation Varying  $S$ ;  $\rho$  from Calibration Point*

To compensate for the error due to traffic density variation, the observed conflicts were adjusted by multiplying by  $\rho$  correction factors. For each case, this factor was simply the

<sup>\*</sup> Aircraft per 10,000 NM<sup>2</sup> is equivalent to the number of aircraft in a 100 NM by 100 NM area. This unit for traffic density is preferred to aircraft per NM<sup>2</sup> because it results in more convenient values (e.g., 7.2 instead of 0.00072). Other studies have also described traffic density in these units for this reason.<sup>41</sup>

ratio of the true SUA subset  $\rho$  value to the calibration  $S_3$   $\rho$  value. For example, the factor for  $S_2$  was 0.63 (from 15.36/24.31), which resulted in the 77 actual conflicts translating to 49 adjusted conflicts – much closer to the ACM prediction of 50. As shown in Figure 3.6, the ACM-predicted values then fit the observed values quite closely ( $R^2 = 99.99\%$ ).



**Figure 3.6** ACM Validation Varying  $S$ ; Conflicts Adjusted to Correct for  $\rho$  Variation

Note that the error introduced by assuming the calibration  $\rho$  when traffic density actually varied could just as well have been corrected by plugging the true  $\rho$  values into the ACM. This would have shifted the predicted points closer to the observed points in Figure 3.5, which is actually a more realistic correction, since the purpose is to use the ACM to predict reality. However, the plot would be discontinuous; instead of a curve, the predictions would only be points corresponding to each pair of  $S$  and  $\rho$  values. Adjusting the observations to fit the predictions is theoretically equivalent, although logically backwards, and was selected to demonstrate that the effects on  $N$  of changing only  $S$  (the analysis originally intended) are in fact represented by the curve generated by the ACM (plotted in Figure 3.6).

These results require clarification. The initial comparison (Figure 3.5) was an attempt to use the ACM to predict changes in conflicts associated with changes in SUA size, assuming a constant traffic density for all SUA sizes. Unfortunately, the actual areas varied in location (mainly shifting eastward off the coast of Florida) as well as size, and it turned out that traffic

density varied significantly with location. This was tantamount to testing the ACM under worst-case conditions, hence the significant error. The second comparison (Figure 3.6) was adjusted to remove the unintentionally varied factor ( $\rho$ ) so that the predictive accuracy of the ACM alone could be checked. This was found to be excellent, validating the ACM as a predictive tool – *provided sufficiently traffic density information is available*. In short, therefore, these results validate the theory behind the ACM, but call for further investigation of sources of traffic density information and subsequent ACM precision to determine the practical usefulness of the ACM for rapid analysis.

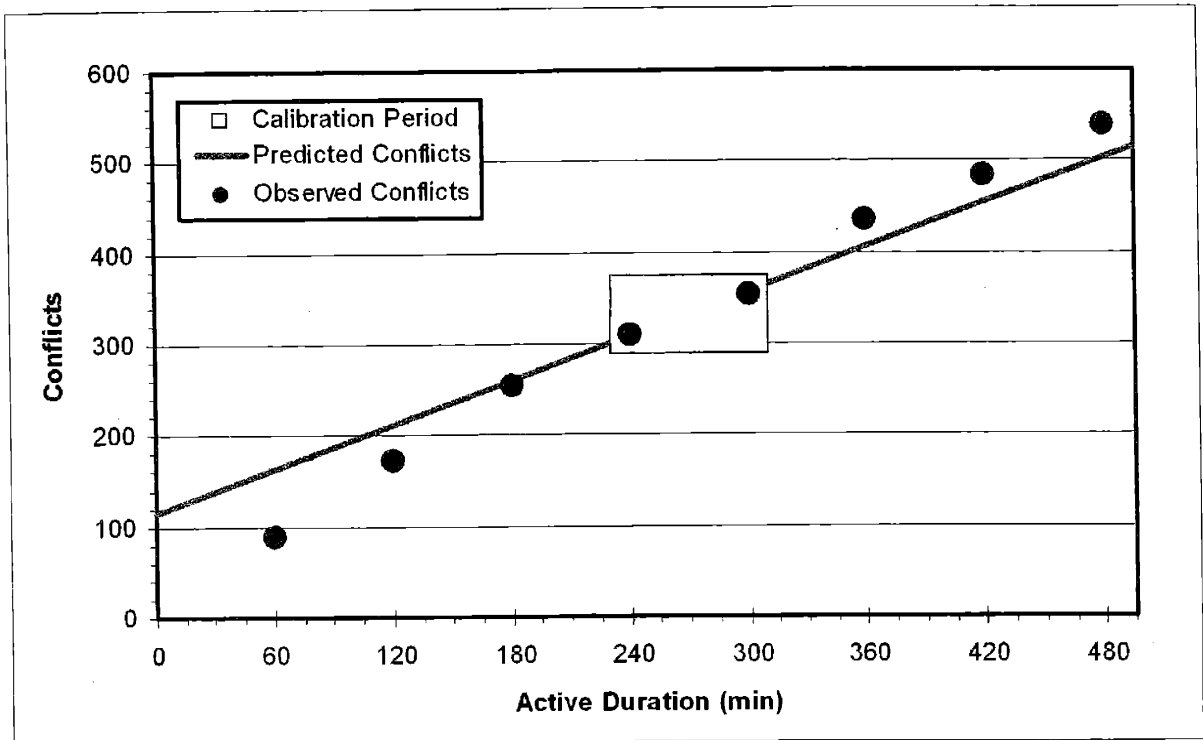
In addition, these results also validate the use of the circular approximation-based estimates of  $a$  and  $\tau$  for the inputs to the ACM. Further improvement in information about these factors does not appear to be warranted.

#### 3.4.4 Varying $T$

For the second set of ACM validation studies,  $T$  was varied while all other parameters were held constant. The SUA subset  $S_3$  from the previous analysis (i.e., containing areas R-2932, R-2933, R-2933, R-2934, and W-497A) was arbitrarily selected for the SUA size. A total time range of eight hours was analyzed, from 0900 to 1700 local time, in one-hour intervals. The two-hour calibration period was located in the middle of this range, with three one-hour intervals on either side.

For the first comparison, the same CRCT calibration point was used:  $\rho = 15.36$  aircraft per 10,000 NM<sup>2</sup> for the interval from 1200 to 1400 local time. For this analysis, however, the ACM was used to predict the accumulation or decline in conflicts as the total active duration increased up to eight hours or decreased to zero. This is plotted in Figure 3.7. To clarify, the 309 conflicts accumulated over the first 240 minutes was taken as the starting point. The two hour calibration period from 1200 to 1400 was used to set  $\rho$ , which determined the slope of the line representing predicted conflicts. This was then used to forecast the growth in conflicts for three hours after 1400, and also to “backcast” the decrease in conflicts to see how well the calibration  $\rho$ -value fit the prior interval. In all, the ACM-predicted values fit the observed values fairly well ( $R^2 = 99.65\%$ ), but the observations appeared to diverge from the predictions, especially in the backcast period, potentially indicating systematic error.

As with the error in the previous validation analysis, it was unclear whether this divergence might be due to a failure of the ACM, or, as was found before, primarily arising from use of calibration  $\rho$  value for the other time periods (listed further below).

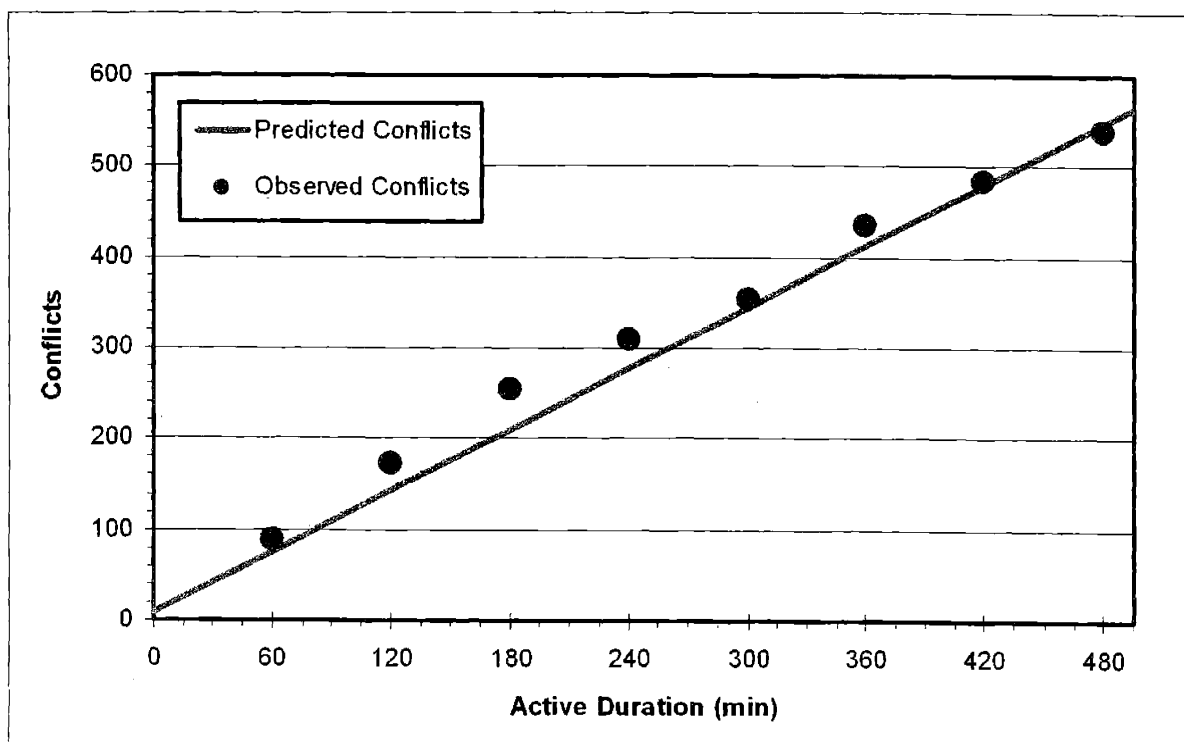


**Figure 3.7 ACM Validation Varying  $T$ ;  $\rho$  from Calibration Period**

To investigate the accuracy of the traffic density calibration, the arrival rate data from CRCT were used to calculate the average traffic density for the other time periods. This produced the average hourly values listed below, and confirmed that applying the calibration  $\rho$  value to other time periods was a source of error (potentially responsible for the divergence):

- 0900 – 1000: 27.78 aircraft per 10,000 NM<sup>2</sup>
- 1000 – 1100: 26.20 aircraft per 10,000 NM<sup>2</sup>
- 1100 – 1200: 25.88 aircraft per 10,000 NM<sup>2</sup>
- 1400 – 1500: 25.57 aircraft per 10,000 NM<sup>2</sup> — *calibration period*
- 1500 – 1600: 15.15 aircraft per 10,000 NM<sup>2</sup>
- 1600 – 1700: 17.36 aircraft per 10,000 NM<sup>2</sup>

To see if the predictive divergence could be corrected by more accurate traffic density information, the overall average for the entire eight-hour interval was used:  $\rho = 21.23$  aircraft per 10,000 NM<sup>2</sup>. As shown in Figure 3.8, the ACM-predicted values then fit the observed values without divergence or systematic error. (Interestingly, however, the correlation remained unchanged, illustrating a limitation of the  $R^2$  statistic.)



*Figure 3.8 ACM Validation Varying T;  $\rho$  from Entire Eight-Hour Interval*

The implications of these results are similar to those from the previous section – the ACM was supported as a predictive model of airspace conflicts, but once again, additional traffic density information was required.

### **3.4.5 Conclusion**

Careful investigation of the conflicts that would arise between actual air traffic and various regions of existing SUA, restricted for different durations, finds the predictions of the ACM sufficiently accurate to support the validity of this model for general predictive use.

Nevertheless, the full value of the ACM in facilitating rapid policy analysis is not yet clear. The very existence of an analytical model provides useful insight into the mechanics of conflict generation, and by extension into disruption costs – a significant contribution. However, it was hoped that the ACM could be used for analyzing specific cases without having to run time-consuming models. If sufficient input information (notably about traffic density) to run the ACM accurately cannot be found without such efforts, the ACM may ultimately end up transferring the modeling burden rather than alleviating it.

## Chapter 4: Technical Analysis

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This chapter presents quantitative analyses of the disruption cost associated with strategic and tactical aerospace traffic management policies under various circumstances. Six factors critically affecting this cost are identified, and the uncertainty and sensitivity related to each is explored. Then scenarios representing four alternative sets of potential developments are constructed, and the disruption cost is computed for each. Finally, the implications of these results for the policy decision are summarized.

### 4.1 Procedure

The first part of the two-phase approach developed in Chapter 2 is the technical analysis, modeling policy options and uncertain factors to calculate quantitative performance metrics. The two basic policy alternatives are strategic separation of air and space traffic by means of Special Use Airspace (SUA), and tactical separation of integrated aerospace operations. Among the uncertain factors affecting the decision are future developments in air traffic, space transportation, and air traffic management (ATM) procedures and technologies.

Efficiency was identified as the issue most likely to help decision-makers compare policy options, and a first order approximation of the total annual disruption cost ( $J$ ) was developed as a reasonable metric. This was described as the product of four factors (Eq. 1):

- $N$  – average air/space traffic conflicts per space transportation event
- $E$  – average space transportation events per year
- $D$  – average traffic disruption (airborne delay minutes) per conflict
- $C$  – average cost per unit disruption (assumed constant: \$62.50 per minute)

The first factor,  $N$ , was further analyzed in Chapter 3, where the Airspace Conflict Model (ACM) was presented (Eq. 10). This was shown to predict the average number of conflicts associated with restricting airspace on the basis of four parameters:

- $S$  – the volume of the restricted airspace
- $T$  – the duration for which the airspace is restricted
- $\rho$  – the average air traffic density
- $\tau$  – the average time for traffic to transit the restricted airspace

All told, this amounts to six factors identified as critically affecting  $J$ : the four contributing to  $N$ , plus  $E$  and  $D$ . (As discussed in section 2.3.3,  $C$  is merely a constant.) Ideally, all feasible values should be investigated in order to comprehensively map the decision space. With this knowledge of all possible combinations of policies and circumstances, it would always be possible to identify the optimal policy, whether seeking the lowest  $J$  (global minimum), a low  $J$  robust to uncertainty (expected minimum), the lowest worst-case  $J$  (minimum regret), etc. But the ranges of values that some factors could achieve individually are quite large, let alone in combination with the other dimensions. This being the case, a logical procedure is to first investigate each factor independently. Technically, the sensitivity of  $J$  to each factor is already known, since  $J$  has been described analytically. But many people (including the author) find it easier to interpret the relationships between factors from graphical depictions than from equations or data tables. Accordingly,  $J$  is plotted over the potential range of each factor, with all other factors held at expected values.

This can be valuable: at a glance, any such plot reveals both the potential range of the plotted factor (reflecting the uncertainty associated with it) and the power of that variation to affect  $J$ . Unfortunately, there are two limitations to this information. First, sensitivity to changes in one variable, holding all others constant, neglects interaction effects. This may be a serious omission; in Complex, Large-Scale, Integrated, Open Systems (CLIOS) such as this, it is rarely possible to change only one factor. Second, the specific values of  $J$  on any given plot are only valid if the values assigned to the other factors are correct. Since the uncertainty surrounding these values is the impetus for this whole approach, this is unlikely. Therefore, the  $J$ -values should be used mainly for relative comparisons, and the sensitivity curves should be viewed as rough estimates, subject to variation if the other factors change. In short, the range-sensitivity charts can provide useful information, but it is important to be cognizant of their limitations.

The technical analysis continues by assessing a few plausible scenarios – combinations of various values for multiple factors, representing “good guesses” about how/why they might change together. These scenarios are not predictions, per se, because there is no assertion that actual events will unfold as they describe. They are only possibilities, though they do usually include those developments that currently seem most probable. But if there are important interaction effects that would not manifest in analyses of one-dimensional variations from the overall average, it is hoped that they will be revealed through the scenarios.

In summary, the technical analysis explores the sensitivity of  $J$  to the range of uncertainty surrounding each critical factor, and then investigates  $J$  for selected scenarios of combined changes. The whole decision space is too large to examine in detail, but it is hoped that this will at least construct a general outline, revealing key features and providing reasonable approximations of  $J$  for developments similar to the base case and the selected scenarios.

### 4.1.1 Investigating SUA Events ( $E$ ) and Disruption ( $D$ )

Chapter 3 developed the ACM to model  $N$ , but no such models have been developed for SUA events ( $E$ ) or disruption ( $D$ ). The approaches used to investigate these factors are introduced below.

$E$  is the only critical factor not modeled analytically in this study. This is primarily because, unlike conflicts or disruption, it is not a function of kinematics. Rather than airspace, traffic patterns, or vehicle performance, the number of space transportation events per year results from complex interactions between political and economic forces and operational constraints. Consequently,  $E$  is assessed by simply considering the values – both historically observed and predicted to occur – under various conditions. While this does not lead to a specific forecast, it does enable description of feasible and expected ranges.

In contrast,  $D$  is generally subject to the kind of analysis used for  $N$ , but is complicated by even greater uncertainty. For any given conflict, calculating the disruption associated with deviating around a region is straightforward. Unfortunately, however, there is no clear basis for choosing any particular conflict resolution procedure, as explained in Chapter 2. The pilot or controller can choose to re-route around the restricted airspace immediately, or to fly closer in hopes it will soon become available; the only official regulation is that the airspace not be entered while restricted.

Consequently, for this analysis all flights are rerouted to minimally circumvent the restricted airspace. This approach offers consistency; with disruption always being only the additional time required to circumvent the SUA, and can be converted to a cost through the use of a single factor. (Ground holds and other aspects of conflict resolution not related to direct airborne delays would require different cost factors, but these are not expected to occur with offshore SUA operations, as discussed in Chapter 2.) By focusing on minimum deviation, this approach also represents a lower bound, which is a reasonable basis of comparison in the absence of information about the average disruption actually involved in such situations.

Even for this standardized conflict resolution procedure, however, the values for  $D$  remain heavily dependent on a variable factor – the range (time or distance) at which action is taken to resolve each conflict. This is known as the Alert Zone range ( $Z$ ). The specific concepts of the Protected Zone and Alert Zone are described in sections 4.2.1 and 4.2.6 below. For this introduction, the main point is that  $Z$  is the independent factor that most heavily influences  $D$  as modeled here. Therefore the sensitivity of  $J$  is analyzed with respect to  $Z$ , rather than  $D$ .

The equation for  $D$  is unwieldy and is therefore presented in the Appendix. In this section, the term  $\{D(Z, R)\}$  is used to represent  $D$  (a complex function of  $Z$  and  $R$ ) in all equations.



## 4.2 Range and Sensitivity

This section investigates six factors of  $J$ , based on  $N$ ,  $E$ , and  $D$  from above. However,  $R$  is used in place of  $S$ , and in an effort to focus on root factors (i.e., the components of the ACM, rather than  $N$ ), relative velocity ( $V$ ) is used for  $\tau$  (from Eq. 9, since  $R = 2a$ ,  $\tau$  is a function of  $R$  and  $V$ ), and  $Z$  is used for  $D$ . These are explained in more detail in their sections below. By substitution,  $J = \rho \cdot (\pi \cdot R^2 + 2 \cdot R \cdot V \cdot T) \cdot E \cdot \{D(Z, R)\} \cdot C$ , using the constant cost  $C$  and six variable factors: radius of restricted airspace ( $R$ ), restricted duration ( $T$ ), traffic density ( $\rho$ ), relative velocity ( $V$ ), annual space transportation events ( $E$ ), and Alert Zone range ( $Z$ ). After the individual analyses, these are combined to assess the overall uncertainty surrounding  $J$ .

As described above, only one factor is varied at a time, while all others are held at “standard” values. The set of standard values is referred to as the *base case*, which was constructed using values around the center of the expected ranges for all factors. (The choice for each factor is described in its section.) Arguments can be made for using other values, but given the uncertainty, this was selected as a way to roughly minimize the overall expected error. The base case consists of the following:

- $R = 40$  NM (equivalent to  $S \approx 5027$  NM<sup>2</sup>)
- $T = 90$  min
- $\rho = 7.0$  aircraft per 10,000 NM<sup>2</sup>
- $V = 450$  knots = 7.5 NM/min (with  $R = 40$ , corresponds to  $\tau \approx 8.4$  min)
- $E = 50$  annual SUA events for space transportation
- $Z = 5 \cdot R$  (with  $R = 40$ , corresponds to  $Z = 200$  NM)

These values result in a base case  $J$  of \$78,594. For comparison, actual operations in 2001 probably involved  $R \approx 90$  NM,  $T \approx 180$  min,  $\rho \approx 8.59$  aircraft per 10,000 NM<sup>2</sup>,  $V \approx 450$  knots,  $E \approx 50$  events, and  $Z \approx 5 \cdot R$ , which produces  $J \approx \$987,000$ . The only available external comparison is a preliminary MITRE study, the results of which (adjusting for  $E$  and inflation) equate to  $J$  for 2001 of  $\$785,000 \pm \$250,000$  for variation in  $\rho$ .<sup>1</sup>

This confirms the notion that SUA disruption is not a problem at present; compared to annual air or space operations a cost under \$1 million is negligible. But it is noteworthy that this cost could be significantly reduced though adoption of the base case. This would involve an SUA of almost half the current size, restricted for half as long, plus a small effort to avoid scheduling space transportation operations during peak air traffic periods – not be a very severe policy shift, but potentially very useful if costs should increase. The reasons for this are revealed below, as the sensitivity of  $J$  to changes in each factor are explored.

#### 4.2.1 Radius of Restricted Airspace (R)

Figure 4.1 plots the disruption cost ( $J$ ) over the full range investigated for the radius of the restricted airspace ( $R$ ): 5 NM to 100 NM. The lower limit was selected because 5 NM is the lateral radius of the Protected Zone (PZ) around conventional aircraft. If any aircraft approaches another more closely than this under normal en-route circumstances (naturally there are exceptions for military operations), it is said to have violated the PZ, which is against Federal Aviation Regulations. If this happens in controlled airspace, an alert sounds in the Air Route Traffic Control Center (ARTCC), immediate action is taken to restore minimum separation, and the responsible controller is subject to disciplinary action. Since managing air and space traffic is likely to involve greater risk and complexity than conventional ATM, the PZs for tactical separation would be larger if any different, so the standard PZ radius of 5 NM is a logical lower bound.

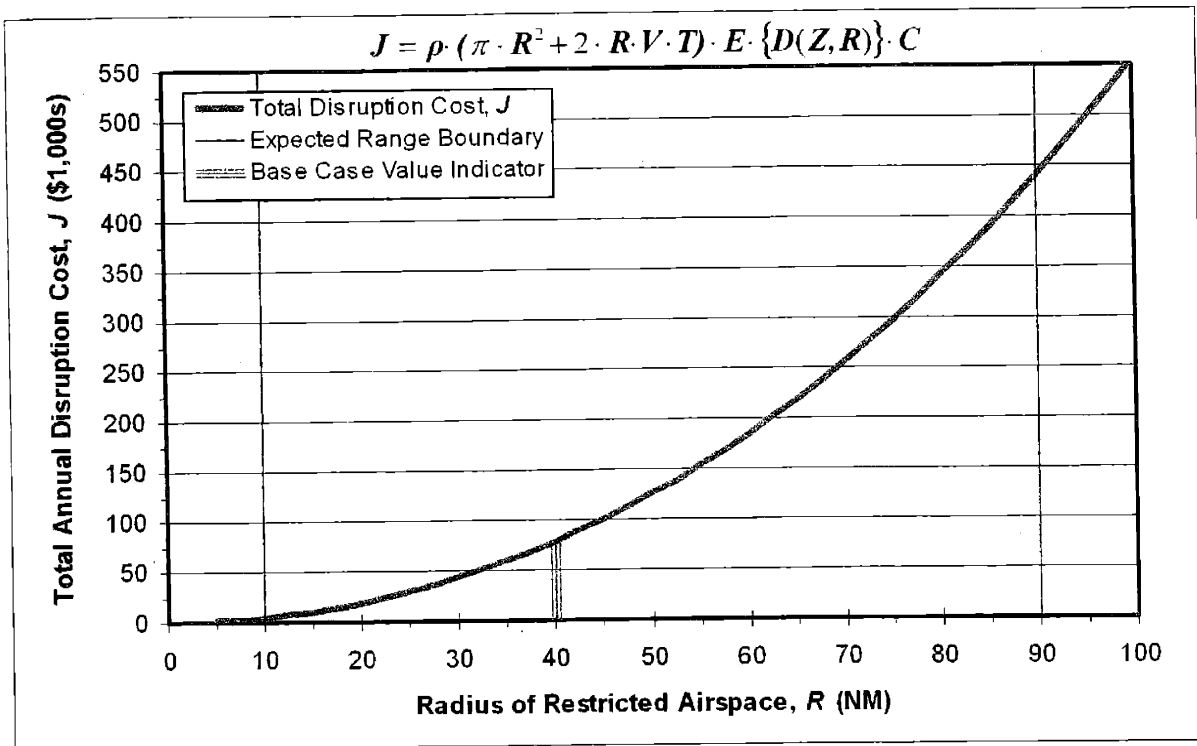


Figure 4.1 Variation in Disruption Cost ( $J$ ) with Radius of Restricted Airspace ( $R$ )

The upper limit of 100 NM was selected as a conservative estimate of the size of the entire SUA around the Kennedy Space Center (KSC) and Eastern Range. (As noted in Chapter 3, the actual geometric area is more precisely approximated by a circle of radius 93 NM, but many controllers reroute traffic conservatively, making the SUA effectively a little larger.) This is slightly larger than the sections of SUA activated for most space operations at the

Western Range. There was no reason to consider greater values of  $R$ , since the drive for this study is to investigate options for reducing the size and duration of restricted airspace. Therefore, the largest status quo is the upper bound for  $R$ .

Also in Figure 4.1, thin, vertical lines can be seen running the height of the plot at 10 and 90 NM. These demark the *expected range*. As it happens, the difference between the expected and extreme ranges is less notable for  $R$  than for any other factor. This is because virtually the entire range is already in evidence, as explained above. Nevertheless, should  $J$  be deemed important enough to warrant action in the near future, the new policy would probably not involve, if tactical, a PZ of  $R$  less than 10 NM (for safety), or if strategic, an SUA of  $R$  greater than 90 NM (for efficiency). Hence the expected range. Within this range, 40 NM was chosen for the base case as a round number near the middle that roughly corresponds to a subset of actual SUA at KSC – the region called  $S_3$  in the previous chapter, which includes all but the large Warning Area, W-497B (Figure 3.4). Hence, should it be determined safe and worthwhile, this reduced SUA could be implemented fairly easily.

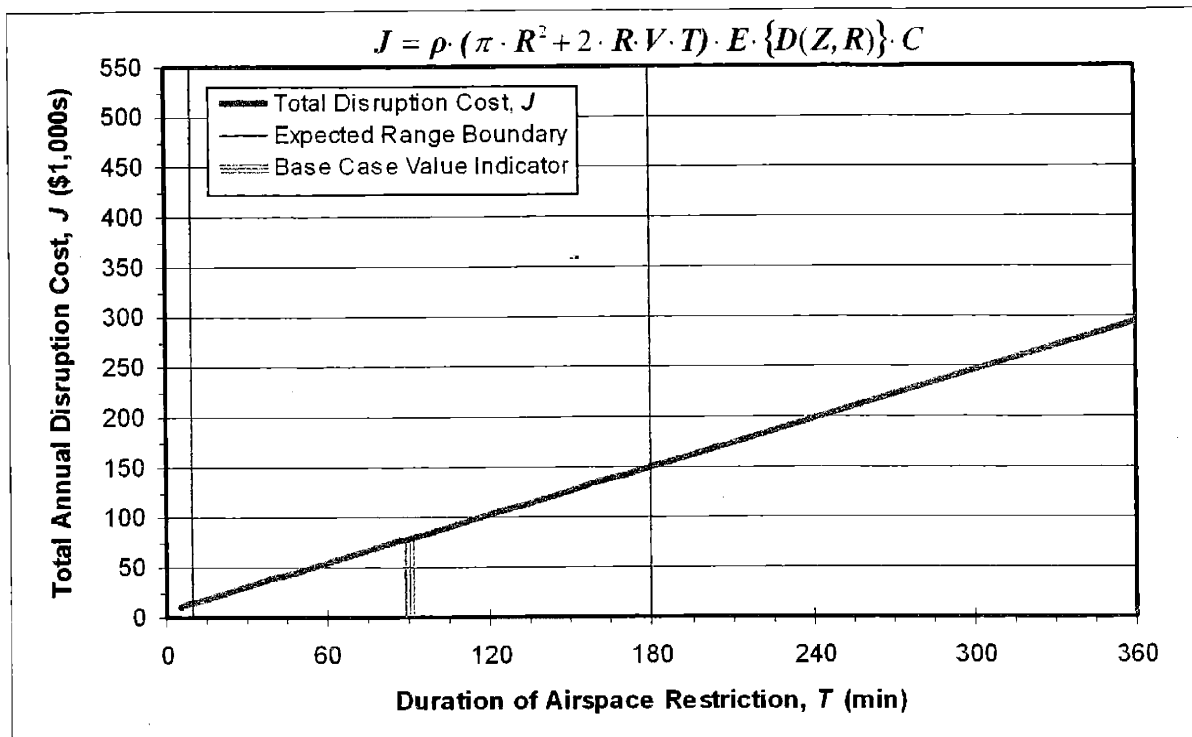
Over both the expected and extreme ranges,  $J$  is observed to increase exponentially with  $R$ . This was predictable, since the ACM describes  $S$  as a factor of  $N$  (Eq. 10), which is in turn a factor of  $J$  (Eq. 1), and  $S$  varies as the square of  $R$ . However, Figure 4.1 is actually depicting even faster growth of  $J$  with  $R$ . This is because  $D$ , another factor of  $J$ , also grows with  $R$ . The combined effect makes  $J$  significantly more sensitive to  $R$  than to any other factor. (The range-sensitivity plots for all factors use the same axes to facilitate comparison.) If  $R$  alone could be varied with the other factors remaining at the base levels, increasing  $R$  over the entire predicted range multiplies  $J$  by a factor of almost 500. This corresponds to an average marginal cost of nearly \$6,000 per NM.

This clearly supports the supposition that it is worth re-examining the current SUA, to see if reduced areas can be used in some situations. It also suggests that tremendous efficiency gains might accompany the adoption of a tactical traffic separation policy, if it could be accomplished with PZs on the order of those used for aircraft today.

#### 4.2.2 *Restricted Duration (T)*

Figure 4.2 plots  $J$  against restricted duration ( $T$ ) over the range of 5 to 360 minutes. The lower bound in this case represents the time required for most vertical space transportation operations to transit the National Airspace System (NAS). For example, the Kistler K-1 vertical takeoff, vertical landing (VT-VL) reusable launch vehicle (RLV), currently being developed, will transit the NAS in 1-2 minutes during ascent and 2-4 minutes during descent (similar to the DC-X test vehicle). Even the Space Shuttle, a vertical takeoff, *horizontal*

landing (VT-HL) partially reusable launch vehicle, transits the NAS in about 1 minute on ascent and 7 minutes during descent. (It should be noted that although the Shuttle lands horizontally, it conducts an unpowered or “dead-stick” landing, essentially without a cruise phase. In fact, it descends at over 10,000 feet per minute and approaches for landing on a 20° degree glideslope, vs. 500 feet per minute and 3° for commercial airliners.) Obviously 5 minutes does not include much of a buffer, which might be desired to ensure the airspace is clear or in case there is a need to pause and then resume a countdown to launch. But it is worth examining as a minimum, for it is a fairly good estimate of the duration for which the airspace is truly needed for many space transportation operations.



*Figure 4.2 Variation in Disruption Cost (J) with Restricted Duration (T)*

The upper limit of 360 minutes, or 6 hours, was selected to approximate the effects of a full SUA restriction (typically 3 to 3½ hours), which has to be cancelled at the last minute and rescheduled for some reason. Unfortunately, this is all too common. Of the first 107 Space Shuttle missions (that is, all through 2001), only 29% launched on schedule. At least 10% had to be rescheduled multiple times.<sup>42</sup> Exactly how long the airspace was restricted in each case could not be determined, so 360 minutes, representing two typical 3-hour durations, was arbitrarily selected for the upper bound. (Reflecting the historical view of SUA as a purely military resource, usage information, if recorded, is not available; even Federal Aviation Administration offices could acquire only a few inconsistent annual summaries.)

10 to 180 minutes was designated as the expected range for  $T$  (denoted in Figure 4.2 by the thin vertical lines). The lower bound was selected as a more realistic operational minimum than the absolute minimum, though admittedly, it would only be feasible with extremely precise position and velocity information for all vehicles, highly reliable space operations, and common air/space oversight for seamless coordination. The expected upper bound was set to correspond to current operations (as was done for  $R$ , above), since again, it is hoped that any change in traffic management policy would be designed to reduce disruptions, i.e., involving shorter durations. Within the expected range, 90 minutes was selected for the base case, because it is fairly central and is conceivable for both shorter SUA operations and longer RLV operations.

On the subject of the last point, it should be mentioned that the expected interval would also accommodate RLV operations, including even horizontal takeoff, horizontal landing (HT-HL) systems with cruise phases of flight. For example, the current Pegasus launch vehicle makes use of a conventional L-1011 aircraft as its first stage, and this typically flies a 90-minute round-trip for a launch operation. Similarly, the Kelly Astroliner concept RLV, which would be towed aloft by a 747, is planned to fly a 2-hour round trip. Thus the 10 to 180-min range should suffice for virtually all foreseeable space transportation operations.

In Figure 4.2,  $J$  can be observed to increase linearly with  $T$ , as the ACM predicts (a constant  $S \cdot \rho$  term notwithstanding). Unlike  $R$ ,  $T$  does not affect any other factors, so its impact on  $J$  is not as great. Over the entire predicted range for  $T$ ,  $J$  varies by a factor of 27.5 (a less than 1:1 relationship because of the  $S \cdot \rho$  term). Yet this is not insignificant. Large savings could still be realized by reducing  $T$ , and even if that is not feasible, it may still be possible to reduce the frequency, and therefore disruption effects, of “false alarms” associated with restricting the airspace and then canceling or rescheduling operations.

### 4.2.3 Traffic Density ( $\rho$ )

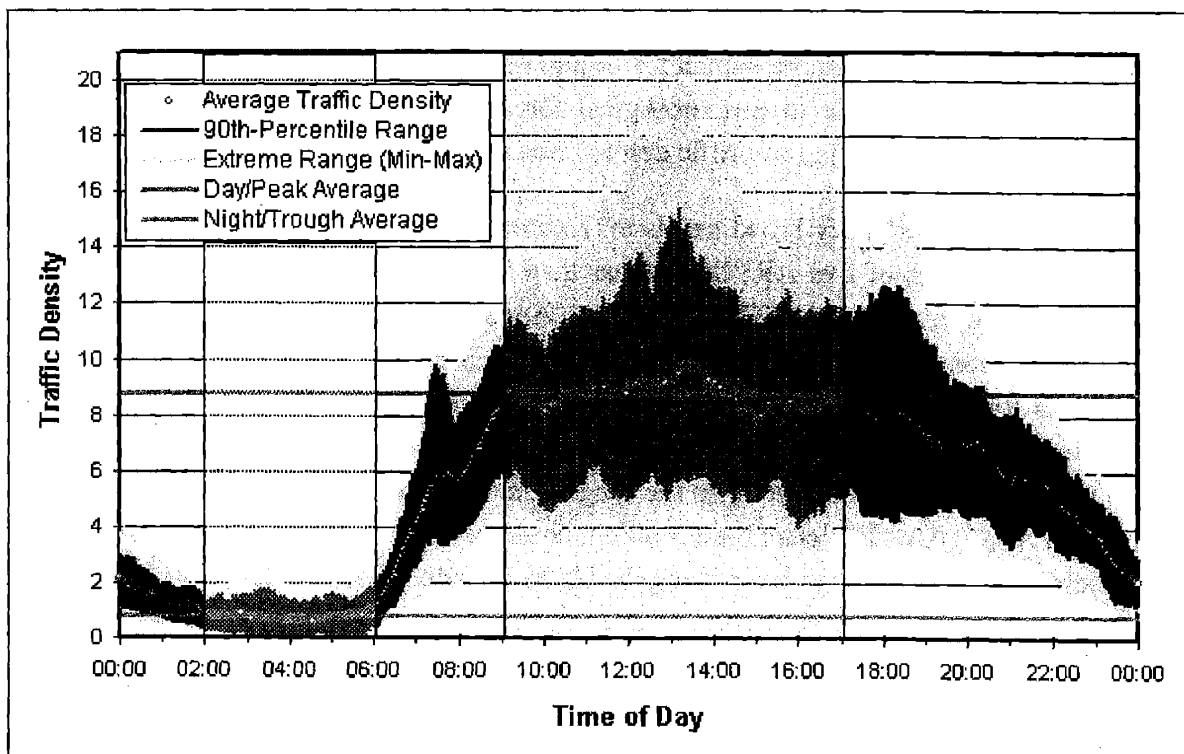
The next factor examined is air traffic density ( $\rho$ ), which is known to exhibit both significant temporal and spatial variation. The temporal variation is primarily due to scheduling. The majority of passenger flights are operated during business hours, and within these, arrivals and departures are frequently coordinated to facilitate connections (this results in “banks” of arrivals and departures, which are especially salient at the hubs of hub-and-spoke networks). The spatial variation is primarily due to air route structure; although some Instrument Flight Rules (IFR) flights are now permitted to proceed directly from origin to destination, most still follow airways from waypoint to waypoint. With thorough knowledge of schedules and airways, it might be feasible to precisely map the temporal and spatial variation in traffic

density for a specific area. While this would improve conflict prediction in that area, it is not clear whether the results would be applicable to any other areas. Furthermore, traffic patterns tend to be highly susceptible to meteorological forces, many of which are unpredictable. Consequently, detailed mapping of traffic density was not attempted for this study.

Instead, in an effort to identify broad trends in temporal variation, the average traffic density was calculated for each of five ARTCCs across the US: Jacksonville (ZJX), Miami (ZMA), Albuquerque (ZAB), Oakland (ZOA), and Los Angeles (ZLA). First, Enhanced Traffic Management System (ETMS) data for commercial traffic was sampled to calculate the instantaneous traffic density for each ARTCC, every five minutes for over one week (the same as used in the ACM validation: March 14 - 21, 2001). These values were then averaged by local time within a 24-hour cycle, so the range could be observed for any given time. For example, the range of traffic densities at 7:00 pm could be observed, with values for each day of the week at that time. This process is applicable to an individual ARTCC or to the average for all five.

Figure 4.3 shows a plot of the aggregated data from all five ARTCCs, which was used to approximate the average system traffic density. The average values (plotted as a bright blue line, in-between the darker areas showing the 90<sup>th</sup>-percentile and extreme ranges) indicate that a typical 24-hour cycle involves a sustained period of high traffic density, basically lasting all day and gradually declining in the evening to a shorter sustained period of very low traffic density late at night, which rapidly climbs back up to the daytime high the next morning. This description was found to fit each of the ARTCCs individually, as well as the system aggregation. They did exhibit different “high” and “low” traffic density levels, and differed somewhat (mainly in the timing) in the transitions between these levels, but the overall cycles were very similar.

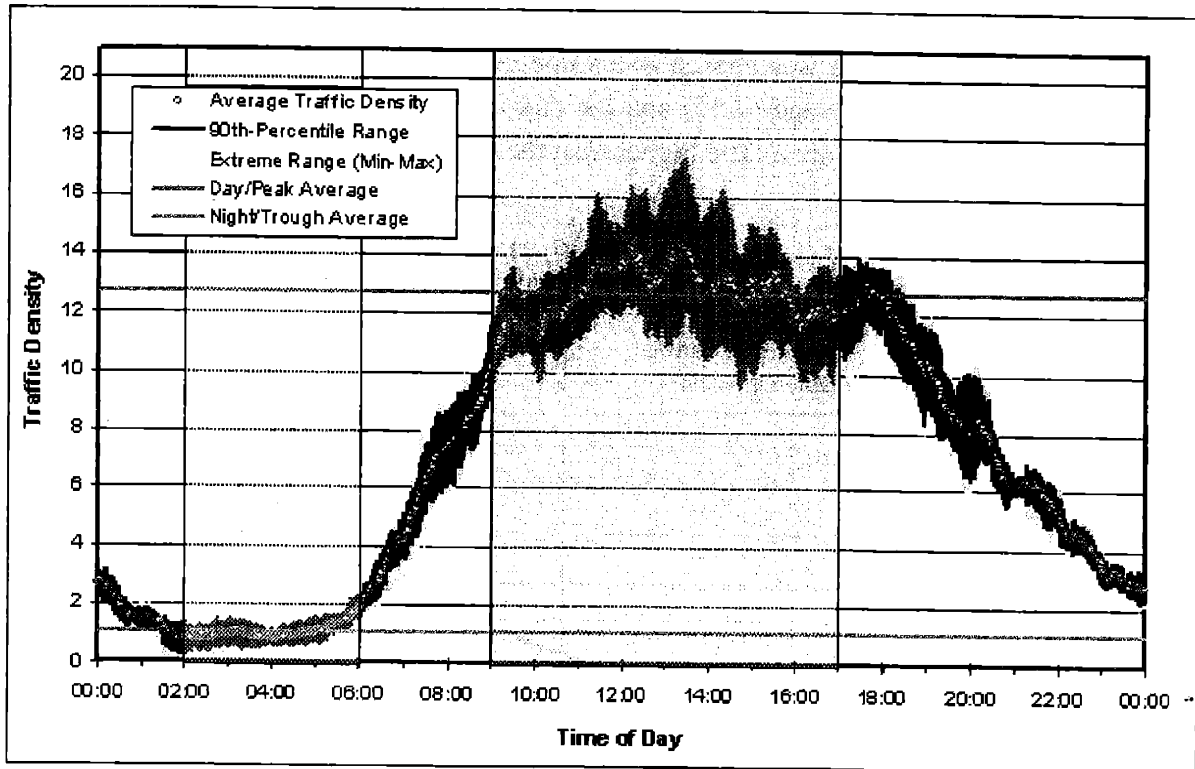
This information about the variations in average traffic density with the local time of day was used to identify two intervals: a daytime peak from 0900 to 1700 (9:00 a.m. to 5:00 p.m.), and a late-night trough from 0200 to 0600 (2:00 a.m. to 6:00 a.m.). During the 8-hour peak period, the mean traffic density was 8.78 aircraft per 10,000 NM<sup>2</sup>, while during the 4-hour trough period it was 0.77 aircraft per 10,000 NM<sup>2</sup>. This indicates that, to first order, any given SUA event during the “day” (peak) would cause over 11 times as many conflicts (involving over 11 times the disruption cost) as the same event during the “night” (trough). Accordingly, the intervals are designated on Figure 4.3 using red and green, to indicate that day and night would be respectively undesirable and desirable times to schedule SUA events, on the basis of expected traffic disruption alone.



*Figure 4.3 Average Traffic Density, Variation with Time (5 ARTCCs, Mar. 14-21, 2001)*

In addition, similar studies were made of the Miami ARTCC alone, which was generally found to have slightly higher traffic densities (the highest of the five ARTCCs surveyed, in fact) than the system averages. This is plotted in Figure 4.4, with the same day/peak and night/trough intervals highlighted that were identified above. Notice the lower variation for a single ARTCC than for the all five. The average day traffic density was 12.71 aircraft per 10,000 NM<sup>2</sup>, while the average night traffic density was 1.06 per 10,000 NM<sup>2</sup>.

Finally, MITRE's Collaborative Routing Coordination Tools (CRCT) model was used to investigate the traffic density within the specific regions of the KSC SUA, as described in Chapter 3. These values were found to vary widely, which was not surprising since the SUA extends from the coast, where there are many airways, to well offshore where there is considerably less traffic. The day/peak averages ranged from 5.02 for offshore areas to 31.64 for inland areas, with an overall average of 10.31 aircraft per 10,000 NM<sup>2</sup>. The night/trough averages ranged from 0.13 to 1.58 (for the same min and max areas), with an overall average of 0.34 aircraft per 10,000 NM<sup>2</sup>.



*Figure 4.4 Avg. Traffic Density, Variation with Time (Miami ARTCC, Mar. 14-21, 2001)*

Taking all of this information into consideration, the full range for  $\rho$  defined for this study was 0.5 to 32.0 aircraft per 10,000 NM<sup>2</sup>, as shown in Figure 4.5, a plot of the variation of  $J$  for this range in  $\rho$ . The lower bound is a compromise; not as low as for the KSC SUA alone, not as high as the Miami ARTCC average, and close to the overall system average. The upper bound was selected to include the highest daytime average recorded, even though this was only for part of the SUA, since this represents actual traffic being affected today, and traffic levels are expected to grow over time.

As with  $R$  and  $T$ , an expected range is also indicated on the plot. The lower bound of 4 aircraft per 10,000 NM<sup>2</sup> was selected because this is about the average  $\rho$  that would be affected at current traffic levels if launches could be coordinated with air traffic – a concept that is explained for the scenarios analyzed later in this chapter. Similarly, the upper bound of 16 aircraft per 10,000 NM<sup>2</sup> was selected because this is about the average  $\rho$  that would exist if launches were not coordinated with air traffic (as has historically been the case) and if air traffic grew at about 4% per year for 15 years – another scenario. This upper bound is admittedly aggressive, but hardly inconceivable; before the terrorist actions of September 2001 led to diminished air travel, most Federal Aviation Administration (FAA) predictions were calling for air traffic to grow even faster, and perhaps double within 10 years.



Finally, within the expected range of 4 to 16, the value of  $\rho$  selected for the base case was 7 aircraft per 10,000 NM<sup>2</sup>. This was chosen as a value fairly near the middle of the range that was between the 24-hour average (7.55) and the day-night transition period average (6.25) for the Miami ARTCC, and only a little higher than the system average (5.57).

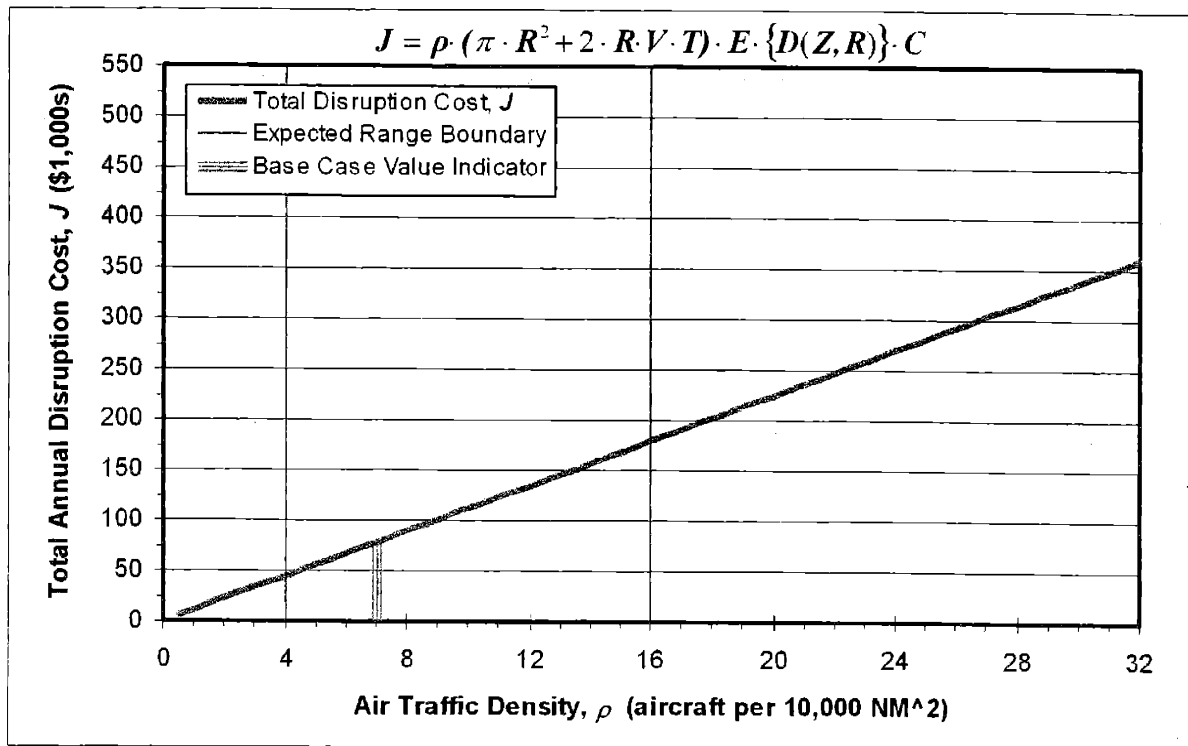


Figure 4.5 Variation in Disruption Cost ( $J$ ) with Air Traffic Density ( $\rho$ )

Figure 4.5 shows  $J$  increasing linearly with  $\rho$ . Varying  $\rho$  over the entire range from 0.5 to 32 aircraft per 10,000 NM<sup>2</sup>, with all other factors at the base case levels, would increase  $J$  by a factor of 64, making  $\rho$  a simple multiplier, as predicted by the ACM. However, this may be a bit misleading. While the number of conflicts is indeed known to increase linearly with  $\rho$ , as shown, most studies have also found that path length grows with  $\rho$ , because more aircraft interact with one another, causing more conflicts that must be resolved. This is not reflected in the calculations for  $D$  used here, however, which represent approximately the minimum deviation required to circumvent an SUA or PZ of radius  $R$ . (There is not general agreement on how much  $D$  grows with  $\rho$  – it is highly situation-dependent – so these calculations simply present a minimum.) Thus, it can probably be expected that  $\rho$  will have a greater effect on disruption cost than shown in Figure 4.5. In fact, this effect increases with  $\rho$ , so at high enough values for secondary conflicts to become significant (certainly above 20 aircraft per 10,000 NM<sup>2</sup>, if not before),  $J$  is probably closer to a function of  $\rho^2$ .<sup>35, 41</sup>

#### 4.2.4 Relative Velocity ( $V$ )

As explained above, the average velocity ( $V$ ) of the air traffic relative to the SUA/PZ, and the radius ( $R$ ) of the SUA/PZ both contribute to  $\tau$  – the average time for air traffic to cross the SUA, which is the fourth component of the ACM. The effects of  $R$  have already been examined, however, leaving  $V$  as the fourth root factor of  $J$  to investigate.

Figure 4.6 plots the disruption cost ( $J$ ) over the range investigated for  $V$ : 50 to 900 knots. In short, this range was selected as generally reasonable for the phenomena under investigation. Some vehicles, such as balloons and gliders, can fly quite slowly; most commercial aircraft cruise at around 450 knots; and supersonic aircraft and especially space launch vehicles can fly considerably faster. However, vehicles traveling at any speeds can approach each other at relative velocities anywhere from  $|V_1 + V_2|$  to  $|V_1 - V_2|$ , depending on their headings. Since this could theoretically range from 0 to twice the speed of the fastest vehicles, it is necessary to consider what  $V$  is used to calculate in order to decide what range is appropriate.

$V$  affects the number of aircraft encountering an SUA while it is active – this is the sense represented by  $\tau$  – and also the amount of disruption associated with deviating to resolve the conflicts (the time required to fly around an area being a function of velocity and distance). Interestingly, these two effects tend to balance one-another: increasing  $V$  causes  $N$  to rise, inflating  $J$ , but also causes  $D$  to fall, reducing  $J$ .<sup>\*</sup> Acting simultaneously, the net result for most values of  $V$  – with all other factors at base case values – is a slight advantage for the latter effect. That is, increasing  $V$  has a net effect of very slightly decreasing  $J$ , but it is nearly flat, as shown in Figure 4.6. An exception to this does begin to manifest at very low speeds: it starts taking so long for the slow air traffic to deviate around the 40 NM radius SUA that the disruption begins to outweigh the minimal savings of fewer aircraft encountering the area, and  $J$  begins to rise at an increased rate. As a result, the lower bound selected for  $V$  could matter, but  $J$  is unlikely to be sensitive to the choice of upper bound.

This being the case, a lower bound of 50 knots was selected on the grounds that this is probably the lowest possible encounter for which the average cost per minute of disruption ( $C$ ) could apply. Although it is possible to conceive of cases involving lower relative velocities, in such cases it seems nearly certain that the aircraft operators would behave differently, charting a different course or flying at a different time, rather than bear the escalating disruption costs.

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<sup>\*</sup> At the same time, increasing  $V$  probably requires more fuel in most cases, raising  $C$ . In fact, beyond a point it would require different fuels – for supersonic and rocket engines – that would likely be much more expensive than ordinary jet fuel. But these engines would have different efficiencies, and supersonic flight would occur at high altitudes where low air density would decrease drag. Hence the net effects on  $C$  are not clear.

The upper bound of 900 knots was selected as the highest relative velocity likely to arise around conventional air traffic. ATM decisions generally integrate vehicles of similar flight characteristics, since common behavior and maneuvers facilitate management, while vehicles of disparate performance frequently fly in separate regions of airspace. Aerodynamic factors contribute to the same effect: supersonic aircraft cruise at higher altitudes than most subsonic aircraft for reasons of drag and efficiency, and as speed increases this becomes critical for withstanding dynamic pressure. Hence it is probably unnecessary to model RLVs at hypersonic velocities in proximity to air traffic, since this is extremely unlikely to be attempted (on technical grounds) or permitted (for safety). But even were this worth considering for some reason, it would not matter: the curve is so flat that the difference in  $J$  between 900 knots and even orbital velocity (Mach 23) is much less than that between 75 and 100 knots. (Again, this is without considering possible variation in  $C$ .)

Hence the full range of  $V$  is 50 to 900 knots, and within this, the expected range is simply 300 to 600 knots, corresponding to the typical range for commercial traffic. The value of 450 knots was selected for the base case, this being about the average cruising speed of most commercial airliners, and observed to fit the ETMS data for actual operations.

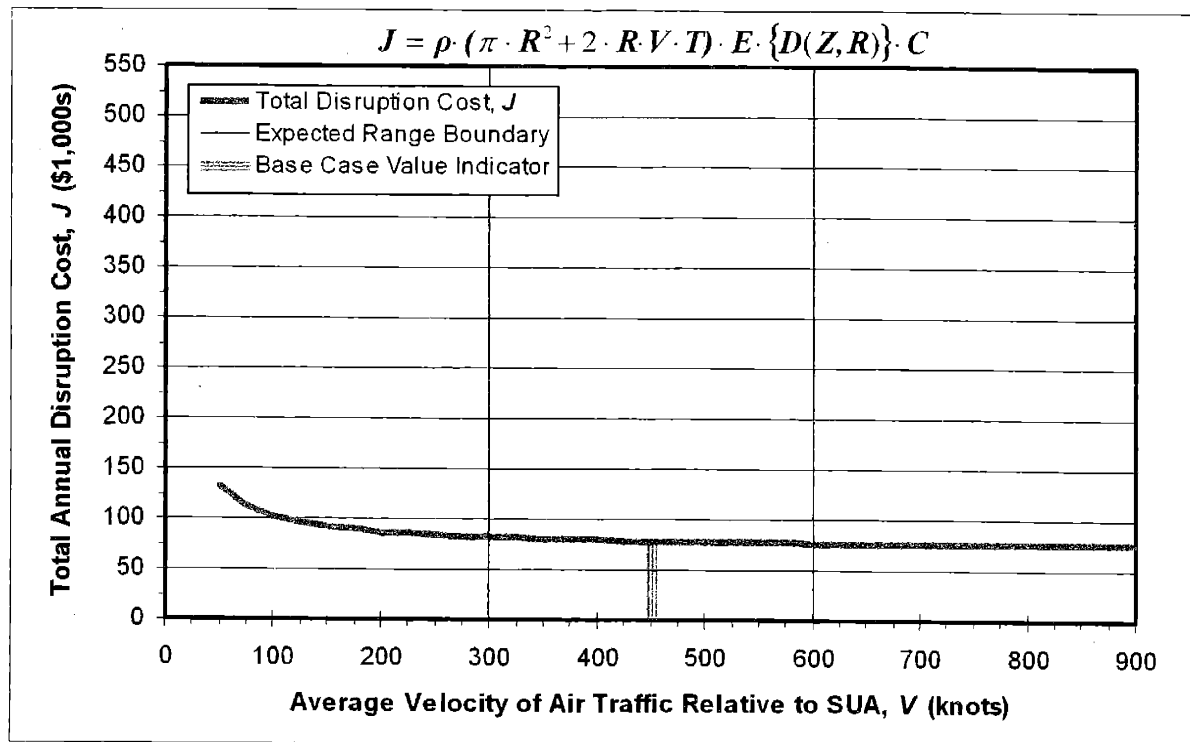


Figure 4.6 Variation in Disruption Cost ( $J$ ) with Relative Velocity ( $V$ )

As explained above, it turns out that  $J$  is highly insensitive to  $V$ , because the two effects of this factor on  $J$  act in opposite directions. Consequently, increasing  $V$  from 50 to about 300 knots will decrease  $J$  by a factor of about 1.6, but continuing to increase  $V$  beyond that will have little effect.

#### **4.2.5 Annual Space Transportation Events ( $E$ )**

The first factor of  $J$  not included in the ACM, the annual number of space transportation events ( $E$ ) will obviously affect the total annual disruption cost. However, it is different from the previous factors in that it is considerably more of an independent variable.  $R$  and  $T$  can be set by policy-makers or traffic controllers;  $\rho$ , while not really directly controllable, is subject to known variation, so timing and location permit indirect control; and  $V$ , though pretty much fixed for the air traffic, is a design parameter of the launch vehicle. In stark contrast to these stands  $E$ , which is only relatively subject to loose and distributed control. Most of this control is divided between the National Aeronautics and Space Administration (NASA) and the Department of Defense (DOD). The Office of the Associate Administrator for Commercial Space Transportation (AST) of the FAA serves an important function in licensing commercial operations (which in 1997 did actually eclipse governmental operations), but this gives AST little power over  $E$ . It could restrict commercial operations by withholding licenses, but it has no means to increase them, and little if any influence over noncommercial operations. There are also significant commercial forces involved, mainly in supplying launch vehicles. In short, what control over  $E$  can be found is divided, and heavily constrained by budgetary and capacity limits.  $E$  is worth examining nevertheless, because a high  $J$  per operation might be acceptable if there are only a few launches per year, whereas even a value of  $J$  currently deemed insignificant could perhaps become prohibitive if a wonderfully efficient RLV were developed, and began flying weekly missions.

Currently, the US conducts roughly 30 to 40 aerospace transportation events per year. Almost all of these are launches; the only exceptions are Space Shuttle re-entries/landings, which number about 6 per year. Attempting to predict future launch rates is something like trying to predict the stock market (ironically, it is subject to many of the same forces); it is amazing how far off even the most careful estimates can become in a very short time. There are a number of reasons for this: commercial opportunities suddenly materialize and collapse; the budgets of government programs vary from year to year; mission timelines and priorities change; and the system capacity depends on all of the above plus many other factors, even including the weather. Fortunately, it is not necessary to predict the exact number of events to investigate the effects of  $E$  on  $J$ . It is mainly necessary to define plausible ranges.

Figure 4.7 plots the variation of  $J$  over the range of  $E$  from 10 to 200 operations per year. This range is based partly on what has been observed in the past, and partly on what has been promised for the future. Historically,  $E$  has fluctuated between 30 and 46 in the last ten years, and between 9 and 77 since the first US launches in 1958. Once RLVs enable more efficient transportation to orbit, most plans call for at least 50 flights per year. The Space Shuttle was originally supposed to achieve 60; the Lockheed Martin VentureStar (concept shelved last year) at least 40; and the Kistler K-1 (currently being developed) up to 52 (from the Nevada launch site alone). So 50 to 100 flights is a popular estimate; given launch and return, this becomes 100 to 200 SUA events per year. 10 was selected as a lower bound because the government alone has sufficient interest in orbital communications, navigation, and surveillance (CNS) missions to maintain at least this many annual launches under almost any foreseeable circumstances. (Even immediately following its most serious space transportation setback, the Challenger disaster, the US managed 9 and then 16 events.) The maximum of 200 accommodates either a very high RLV flight rate, or a moderate rate that also includes rescheduled operations. The expected range was then defined as 30 to 100 to include almost all historical years and non-revolutionary plans (no RLVs or space wars) and again allow for rescheduled events. 50 was picked for the base case, because this seems reasonable given that recent years have involved about 40 operations (33 launches and 6 Shuttle landings) and an unknown but potentially significant SUA event rescheduling rate.

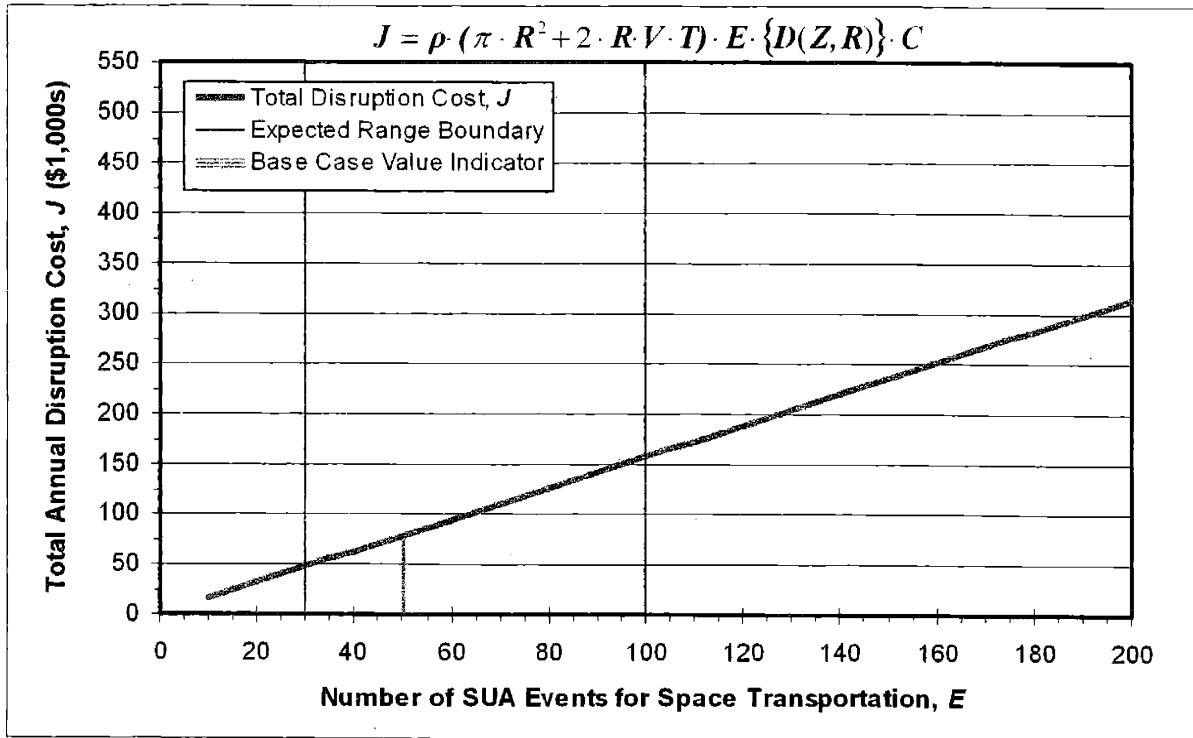


Figure 4.7 Variation in Disruption Cost ( $J$ ) with Space Transportation Events ( $E$ )

Figure 4.7 shows  $J$  increasingly perfectly linearly with  $E$ , as one would expect from a simple multiplier (Eq. 1). Consequently, an increase from the minimum 10 to the maximum 200 events would multiply  $J$  by a factor of 20. This makes  $E$  a significant factor so far, although nowhere near as potent as  $R$ .

#### 4.2.6 Alert Zone Range ( $Z$ )

The final critical factor underlying  $J$  is the Alert Zone range ( $Z$ ). As explained in section 4.4.1,  $Z$  is the controllable variable determining  $D$  (under the conflict resolution approach adopted for this study), and is therefore the appropriate focus, just as  $V$  was for  $\tau$ . The Alert Zone (AZ) is a complement to the Protected Zone (PZ) in the conflict detection and resolution theory developed for tactical traffic management. As described in section 4.2.1, the PZ defines the minimum separation between vehicles; under normal circumstances this should never be violated. The AZ is a larger area around a vehicle, extending primarily in front (technically, in the direction of the relative velocity toward the conflict), but with specific geometry determined by speed, maneuverability, and conflict resolution strategy. The PZ, AZ, and  $Z$  are illustrated in Figure 4.8 below. Its function is to define the spatial envelope indicating the need to take conflict-resolving action to avoid violating the PZ. In the simple case of a head-on conflict, therefore,  $Z$  is simply the minimum range to the SUA (or other vehicle) before which an avoidance maneuver must be initiated in order to resolve the conflict without violating the SUA/PZ.

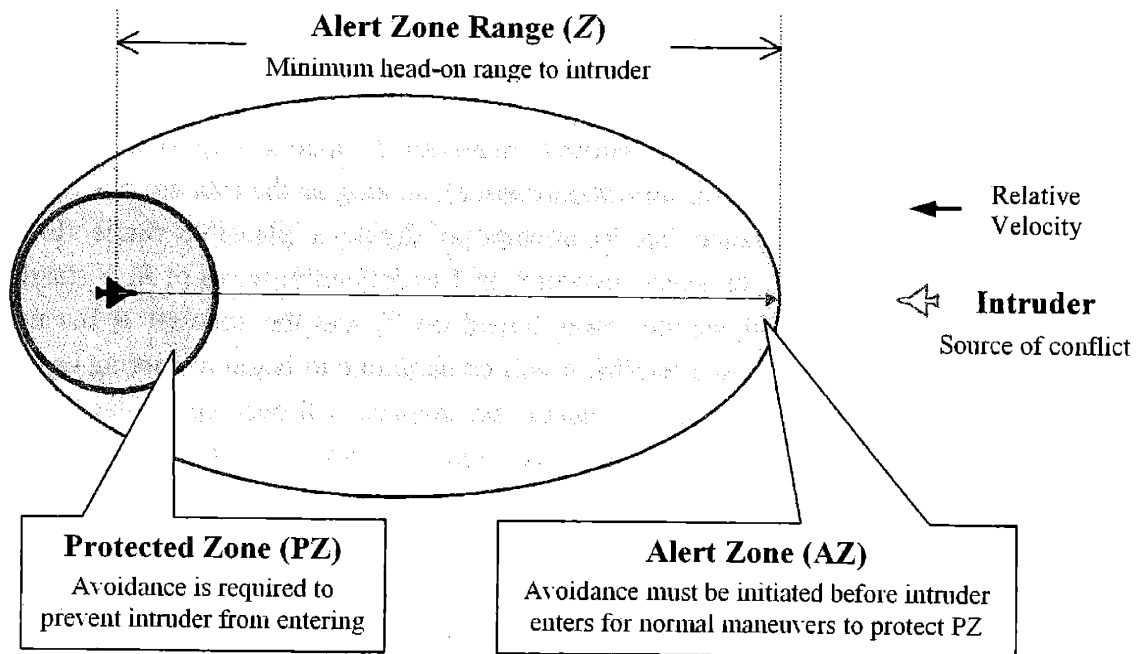


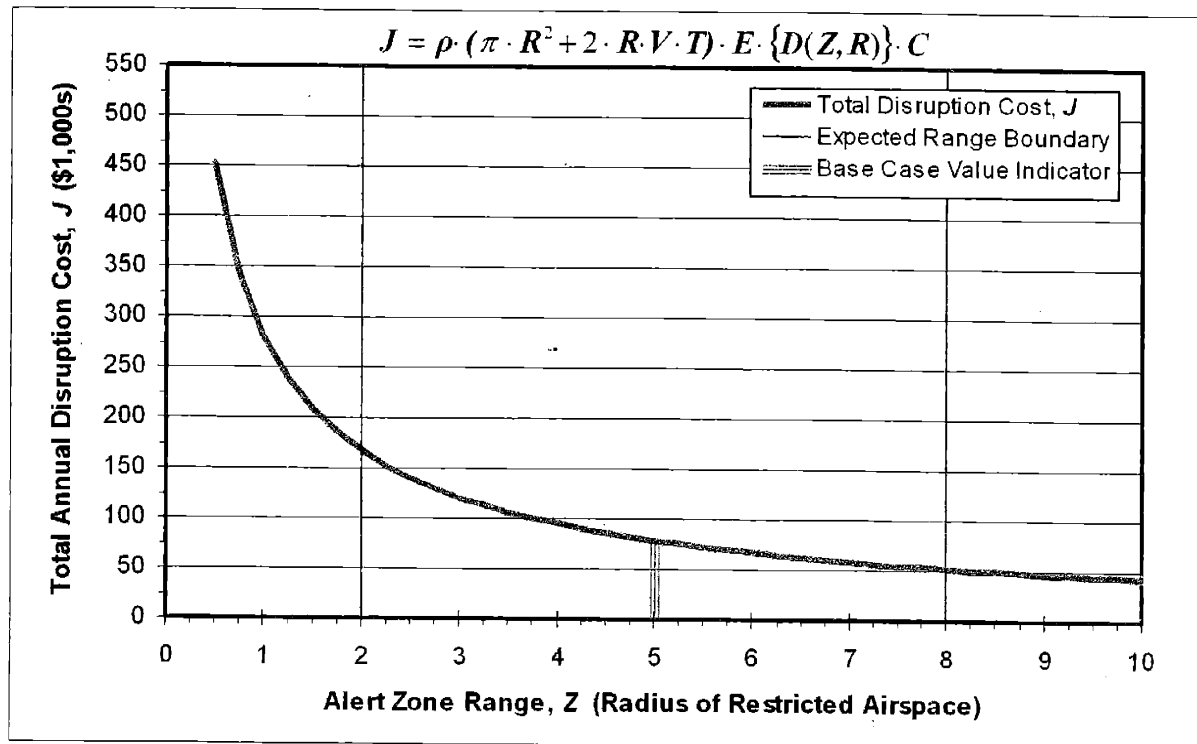
Figure 4.8 Illustration of the Protected Zone, Alert Zone, and Alert Zone Range ( $Z$ )

In practice, determination of the optimal value for  $Z$  can be quite complicated (especially for complex conflict scenarios). If  $Z$  is too short, there will not be enough time to maneuver properly to resolve the conflict – this is known as a “missed detection.” A large value of  $Z$  is also advantageous because, unless the conflict geometry changes, the sooner an avoidance maneuver is initiated, the lower the total path extension (i.e., the lower the  $D$ ) required to resolve the conflict. On the other hand, it is also undesirable to make  $Z$  any longer than necessary, because the longer  $Z$  is, the greater the chance of a “false alarm” – an alert regarding a conflict that ends up requiring no action, precisely because the conflict geometry changes. The other vehicle may change course in an active attempt to resolve the same conflict, but also quite possibly because that was the intent of the other pilot all along. The high speeds of modern aircraft can result in very high relative velocities between vehicles. Consequently, an aircraft in proximity to other traffic could rapidly threaten numerous conflicts simply by conducting a harmless turn. Thus the proper choice of  $Z$  requires striking a careful balance between the probabilities of missed detection and false alarm, the severity of evasive maneuvers, and the average path extension. (See Appendix for more details.) Fortunately, as in the other cases, it is not necessary to optimize this function to assess its importance to this policy decision. It is only necessary to define a reasonable range.

Ideally,  $Z$  should probably be defined in units of time, rather than distance, because timing actually defines conflicts and AZs, but this matters little if only one factor is modified at a time (with a constant  $V$ , any distance can simply be converted to time). As a result, it is convenient to define  $Z$  in terms of  $R$ , to reflect the fact the desired time to initiate conflict resolving maneuvers depends upon the size of the area to be avoided. This helps to limit the severity of the maneuver, but is much more important (in this context) for minimizing the additional distance flown,  $D$ , and hence  $J$ .

Unfortunately, it is difficult to identify a “correct” range for  $Z$ , since it is up to the individual air traffic controllers (or pilots, in uncontrolled airspace), as long as the PZs are not violated. Consequently, there is little choice but to attempt to define a plausible range through consideration of the speeds and distances involved. If  $Z$  is defined in terms of  $R$ , it stands to reason that the largest  $R$  should set the lower bound on  $Z$ , and the smallest  $R$  the upper bound. If the largest  $R$  can be up to 100 NM, it will be desirable to begin re-routing early, to minimize  $D$ , but not too early if there is a chance the airspace will become available by the time it is approached. Thus  $0.5 \cdot R$  seems conceivable; 50 NM is still quite a distance; depending on  $V$ , it could be up to 60 minutes away, and at least 5 minutes. For the upper bound,  $R$  could be as small as 5 NM, but this would be the PZ of another aircraft. It could be closing at up to 900 knots, in which case even  $10 \cdot R$  would yield only 3 minutes, 20 seconds.  $0.5$  to  $10 \cdot R$  is quite a range, given the range of  $R$ , but not unreasonable for the extremes.

Within the full range of  $0.5$  to  $10 \cdot R$ , the expected range was defined from  $2$  to  $8 \cdot R$ . Upon consideration of other possible cases, this range seems reasonable most often, whereas the extremes are hard to justify except for the unlikely cases used to develop them. For the other factors at base case values, for example, this results in a decision range of  $80$  to  $320$  NM, which corresponds to  $11$  to  $43$  minutes – probably a reasonable range. The base case for  $Z$  was selected exactly in the middle of the expected range, because  $5 \cdot R$  seems appropriate for a broad range of cases.



**Figure 4.9 Variation in Disruption Cost ( $J$ ) with Alert Zone Range ( $Z$ )**

Figure 4.9 illustrates the variation in  $J$  associated with the range of  $Z$  defined above. Like  $V$ , this factor varies inversely with  $J$  (except that this came as no surprise for  $Z$ ). The overall range multiplies  $J$  by a factor of 10 as  $Z$  decreases from greatest to smallest. This is equivalent to the sensitivity observed for  $E$ , which was expected since  $Z$  determines  $D$ , which is likewise a simple factor of  $J$ . (However, the sensitivity of  $J$  to the expected range of  $E$  is slightly greater than that for expected range of  $Z$ .)



#### 4.2.7 Combined Uncertainty in $J$

The overall and expected ranges for each of the six critical factors have been discussed above, and the sensitivity of  $J$  to the variation of each factor has been analyzed individually. To summarize this information for the full ranges:

- $R = 5$  to  $100$  NM  $\rightarrow J = \$ 1,137$  to  $\$553,960$  (factor: 487.4)
- $T = 5$  to  $360$  minutes  $\rightarrow J = \$10,687$  to  $\$294,298$  (factor: 27.5)
- $\rho = 0.5$  to  $32$  ac/10k NM<sup>2</sup>  $\rightarrow J = \$ 5,614$  to  $\$359,288$  (factor: 64.0)
- $V = 900$  to  $50$  knots  $\rightarrow J = \$75,248$  to  $\$132,137$  (factor: 1.8)
- $E = 10$  to  $200$  events/year  $\rightarrow J = \$15,719$  to  $\$314,377$  (factor: 20.0)
- $Z = 10$  to  $0.5 \cdot R$   $\rightarrow J = \$42,263$  to  $\$452,172$  (factor: 10.7)

These ranges can be combined to describe enormous variation in  $J$ . Figure 4.10 plots  $J$  for combinations of all factors, grouped from their best case (lowest  $J$ ) to worst case (highest  $J$ ) values. The y-axis is logarithmic to best display the complete range, over which  $J$  varies by 9 orders of magnitude: 53 cents to nearly \$300 million. Of course, the circumstances producing these extremes, though not impossible, are far too unlikely to affect the policy decision.

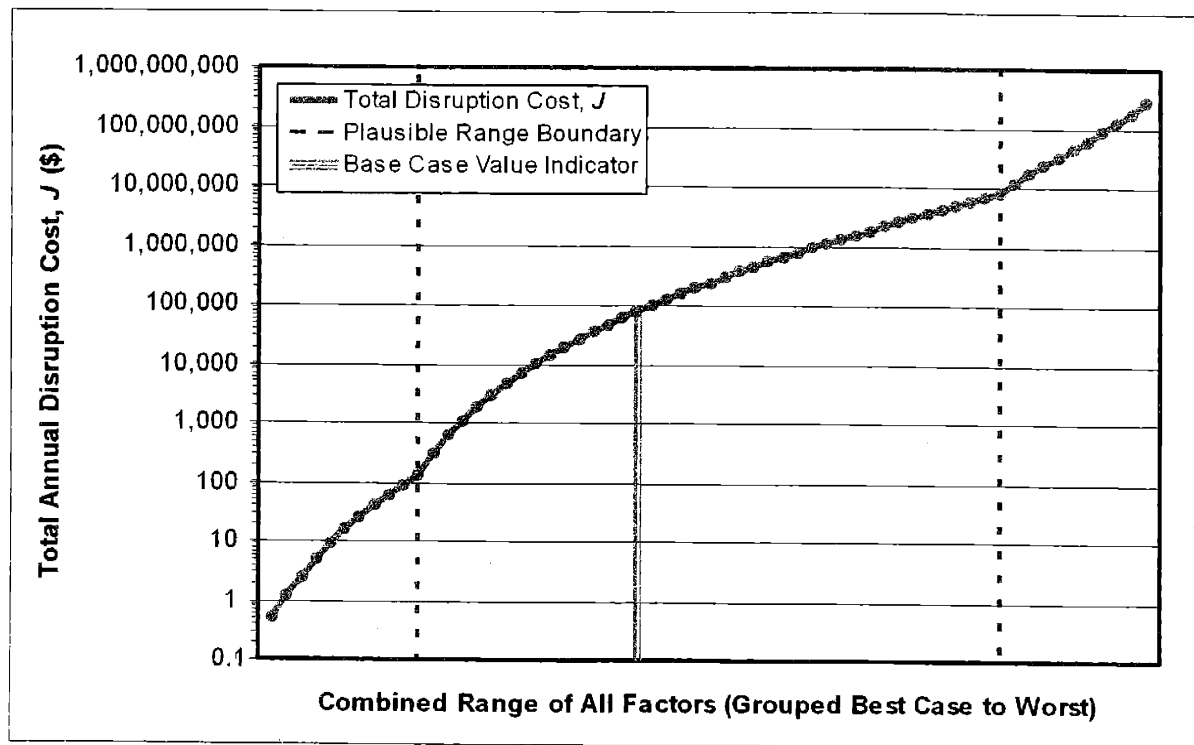
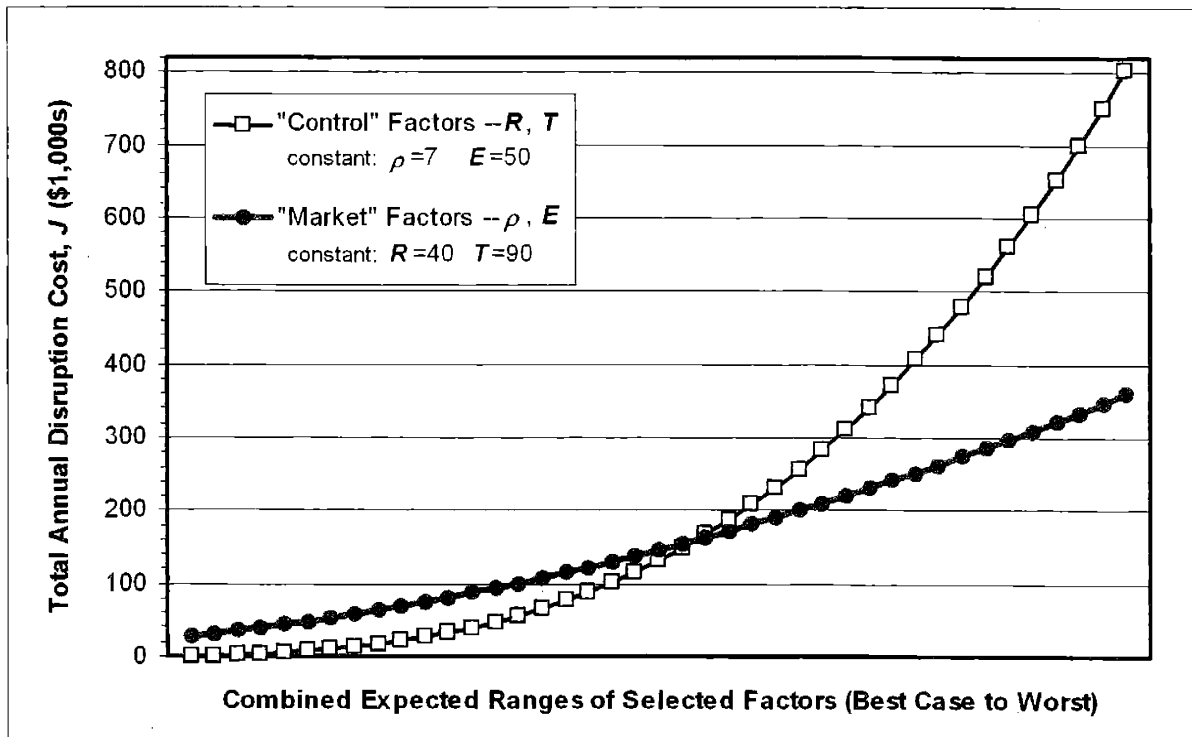


Figure 4.10 Overall Range of Disruption Cost ( $J$ ) Due to Uncertainty in Factors

Related to the expected ranges shown on the plots for the individual factors, a “plausible” range is demarked by the dashed vertical lines in Figure 4.10. This range is comprised of the combinations of all factors varying from their best case to worst case expected values. It is important to note that this is not the same as a truly expected range for  $J$  (hence the different designation), as it remains doubtful that the lowest or highest expected values for the individual factors would coincide. Nevertheless, it supports the notion that significant uncertainty surrounds  $J$ ; this “plausible” range still spans four orders of magnitude, from just \$130 to nearly \$8.2 million. This whole range should not be considered likely, but  $J$  could certainly vary significantly from the base case value of \$78,594 (or the current \$987,000).



*Figure 4.11 Expected Range of  $J$  Associated with “Control” and “Market” Factors*

As a final attempt to clarify the range-sensitivity behavior of  $J$ , combinations of the expected ranges of “control” and “market” factors can be explored.  $R$  and  $T$  can be designated control factors because they are the principal variables directly set by a given policy – the size and duration of restricted airspace. In contrast,  $\rho$  and  $E$  can be called market factors because they represent the behavior of the air and space transportation markets, and are in a sense the least directly controlled aspects of the policy decision. As Figure 4.11 illustrates, the sensitivity of  $J$  to the expected range of control factors is two order of magnitude greater than that to the expected range of market factors. This implies that the factors policy-makers can directly control are more important than those they cannot, which is encouraging.

The final point in this section is that these range-sensitivity results indicate that  $J$  is considerably more sensitive to changes in some factors than others.  $J$  was found to be by far the most sensitive to SUA radius and least sensitive to relative air traffic velocity. The next most powerful factor was traffic density, which, although a very distant second as modeled above, could in fact be more important, especially at higher values, if it also manifests increasing effects on disruption, as discussed. The sensitivity of  $J$  to the other three factors was not insignificant, but simply linear and therefore considerably less than that to SUA radius.

In short, this suggests the most important finding so far: that the overall policy decision may “boil down” primarily to optimal management of  $R$ , a possibility that can be tested through analysis of properly designed scenarios in the following section.

### 4.3 Scenario Assessment

As explained in the beginning of this chapter, the purpose of this section is to complete the technical analysis by assessing a few scenarios, in each of which multiple factors are varied simultaneously to represent a reasonable set of potential developments. Ordinarily, the principal goals of this exercise are (1) to see if any important interaction effects arise, and (2) to see how sensitive the final decision turns out to be, relative to the assumptions which are varied to develop the different scenarios. In this case, however, the range-sensitivity analyses of the previous section suggest that one consideration may dominate all others: the radius of the restricted airspace,  $R$ . Because this would be quite important, if actually true, the scenarios should be developed specifically to test this hypothesis.

In general, the first step in constructing scenarios is to think of some plausible, preferably diverse, sets of developments that could have interesting implications for the decision in question. For the choice between strategic and tactical aerospace traffic management policy options, probably the single most important potential development would be the successful demonstration of a truly efficient RLV, so this possibility must certainly be investigated. But other than this, most interesting circumstances simply relate to notable growth or decline in various factors, such as traffic density. In the absence of other information, it would make sense to construct a few scenarios to investigate these situations. Given the impetus to test the dominance of  $R$ , however, the logical procedure for this analysis is to develop scenarios, with and without highly efficient RLVs, in which either  $R$  or a logical combination of other factors can vary. This should produce the desired information, both for the general decision and the specific importance of  $R$ .

One attempt to carry out this procedure results in the following four scenarios, the details of which are described below:

- Scenario I – Improved SUA timing (all other developments nominal)
- Scenario II – Reduced SUA/PZ size (all other developments nominal)
- Scenario III – Revolutionary RLVs with improved SUA timing
- Scenario IV – Revolutionary RLVs with reduced SUA/PZ size

#### ***4.3.1 Space Transportation Events***

Scenarios I and II involve the current “fleet” of expendable launch vehicles (ELVs) plus the Space Shuttle. Events are modeled by starting with 30 in 2001 and assuming 2% annual growth (as a compromise between 3% forecasts and actual recent declines). However, since the new NASA administrator has just announced that the Space Shuttle will henceforth fly only four missions per year as a cost-controlling measure, only the number of launch events is modeled as growing at 2% (starting with 24 in 2001). A constant four events per year are added to represent the Space Shuttle return operations.

Scenarios III and IV are to represent the development of revolutionary RLVs, which would theoretically fly at least 50 missions per year – but not immediately. An evolution of 6% annual growth in total space transportation events is modeled. RLVs fly four operations in 2002 and then enjoy 50% growth per year, subject to the limitation that they cannot account for more than 95% of the launches of any given year. Although an artificial constraint, this limitation represents two real forces that would have roughly this effect: (1) production lines would continue to supply expendable launch vehicles (ELVs) for at least a few years, to be used as planned for many of the missions already manifested for them; and (2) at least a few ELVs would probably be ordered and launched each year indefinitely, so the government could avoid becoming dependent on a single launch system (a policy decision in force since the Space Shuttle Challenger disaster). All told, this amounts to 14 years of steadily ramping up to reach an annual flight rate of 50.\* Meanwhile, Space Shuttle operations are modeled as gradually phased out over six years. This may seem abrupt, but it is in NASA’s interests to use the most efficient vehicle and to eliminate the costs of operating the Shuttle quickly.

Finally, the number of SUA events modeled for each year was 10% more than the predicted number of space transportation operations, to represent rescheduled operations. (If historical Shuttle rescheduling is a valid indicator, this is quite conservative.)

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\* All of this growth in demand is justified by assuming lower launch prices offered from the start by the more efficient RLV, with the prices continually falling as more missions are flown per year.

### 4.3.2 Traffic Management Policy Options

Two traffic management policy options are listed among the four scenarios: “improved SUA timing” and “reduced SUA/PZ size.” Scenarios I and III involve improved SUA timing, which actually consists of two procedures. The first involves attempting to coordinate space transportation events with air traffic, so as few events as possible take place during the maximum  $\rho$  “day” period, and as many events as possible take place during the minimum  $\rho$  “night” interval. Of course, it will not be possible to schedule all events this way. Historically, the distribution of Space Shuttle events has been 43% during the “day,” 9% at “night,” and 47% during the transition intervals. For Scenarios I and III, it is assumed that 50% of events can be scheduled at “night,” and only 10% need take place during the “day.” This distribution is applied to the average  $\rho$  values, which are assumed to grow at a rate of 3% per year – approximately the average air traffic growth rate over recent years (not including 2001, for which data is not yet available). Coordination in this manner reduces the average  $\rho$  values to only half of those produced by the historical distribution.

The second procedure in the improved SUA timing policy involves reduced durations associated with SUA activation. Four reduced values for  $T$  are modeled – 15, 45, 90, and 120 minutes – in addition to the current duration of 180 minutes (current case shown with and without schedule coordination). Scenarios I and III hold  $R$  at the current value of 90 NM.

In contrast, Scenarios II and IV involve the reduced SUA/PZ size traffic management policy. This investigates four reduced values for  $R$  – 10, 25, 50, and 75 NM – in addition to the current radius of 90 NM. In these scenarios, the scheduling of space transportation events is not coordinated with air traffic (the historical distribution is applied to the average  $\rho$  values, which are assumed to grow at 3%), and  $T$  is held at the current standard of 180 minutes.

Finally, for all four scenarios,  $V$  and  $D$  are modeled at their base case levels of 450 knots and 5  $R$ , respectively. To compare the scenarios over time,  $J$  is calculated using the appropriate factor values for each scenario and year, as described above, from 2001 through 2016. The results are presented below.

### 4.3.3 Quantitative Results

Figure 4.12 through Figure 4.15 plot the results for Scenarios I through IV, respectively, and appear consecutively on the following pages to facilitate comparison between scenarios. Note that the largest cases (current values:  $R = 90$  NM,  $T = 180$  min) of Scenarios I and II are identical, as are those of Scenarios III and IV, while the two sets differ only in the growth rate of  $E$  over time (the effect of revolutionary RLVs). Discussion of these results follows.

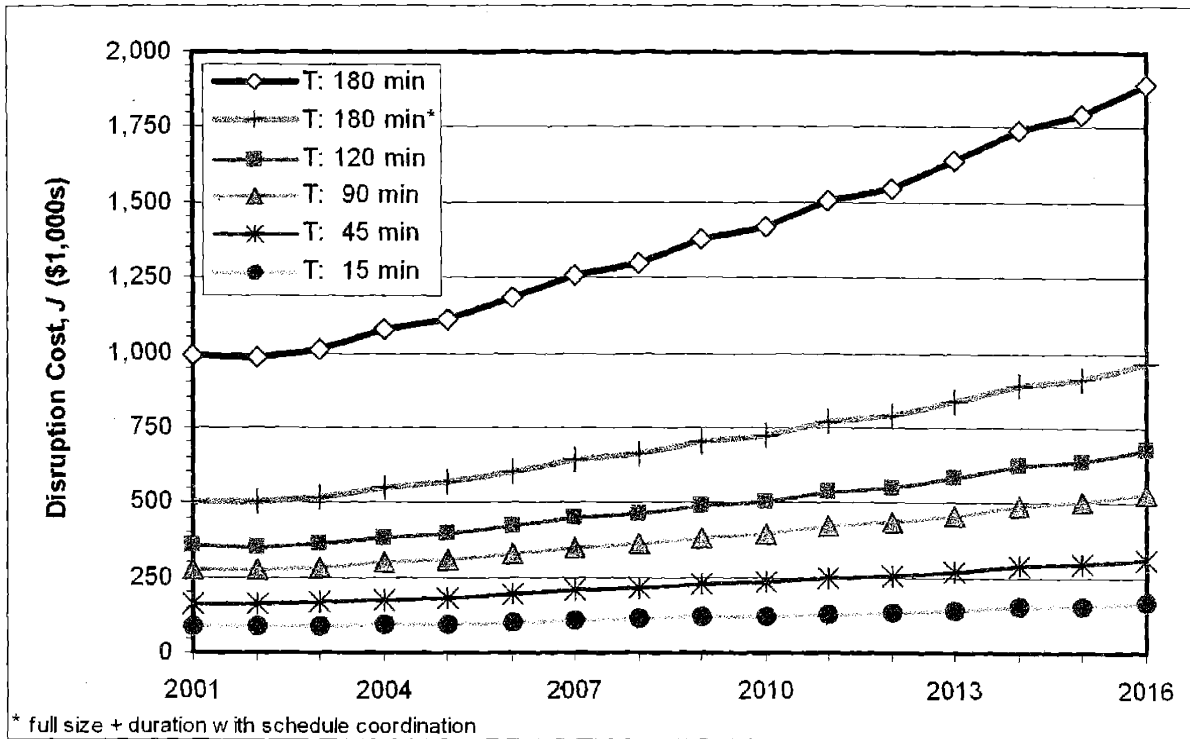


Figure 4.12 Scenario I: Improved SUA Timing (other factors nominal)

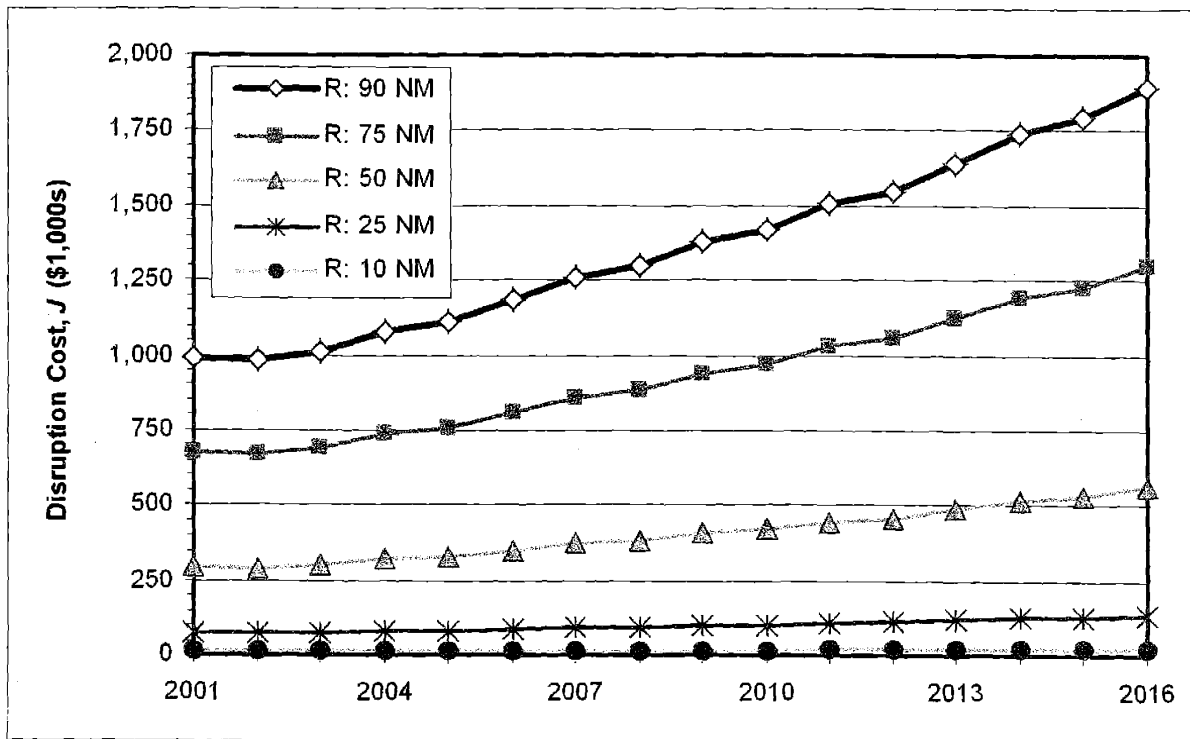


Figure 4.13 Scenario II: Reduced SUA/PZ Size (other factors nominal)

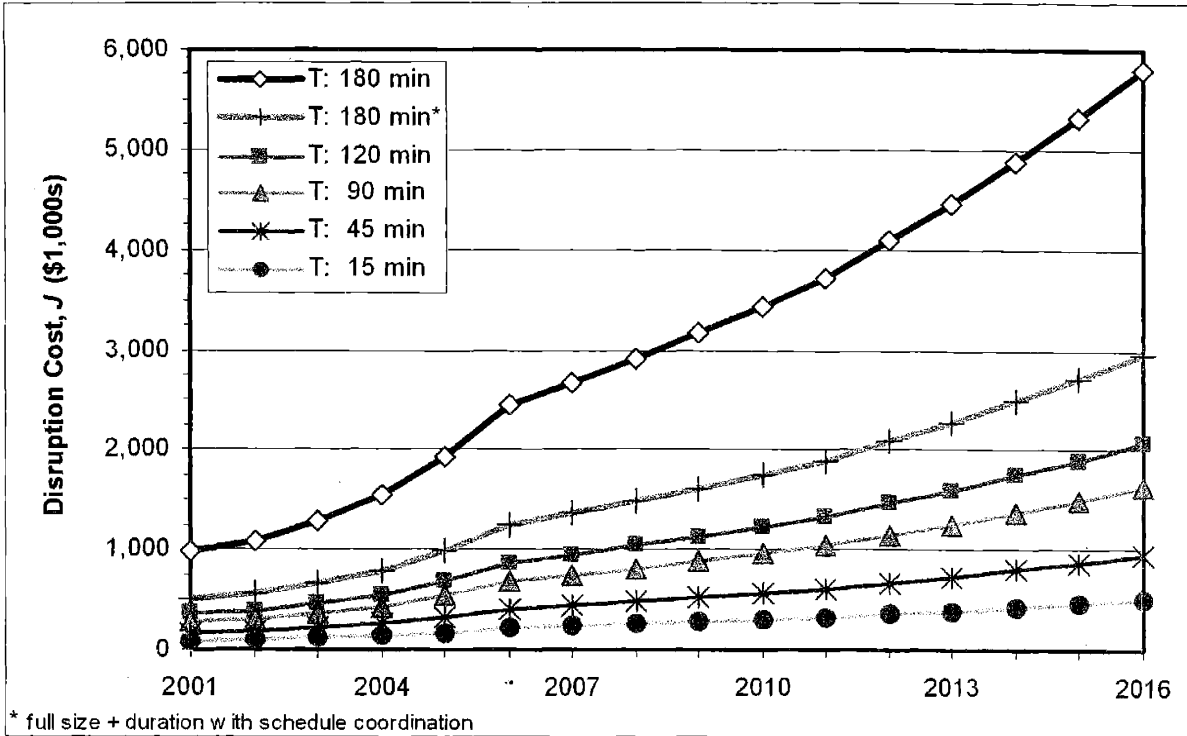


Figure 4.14 Scenario III: Revolutionary RLVs With Improved SUA Timing

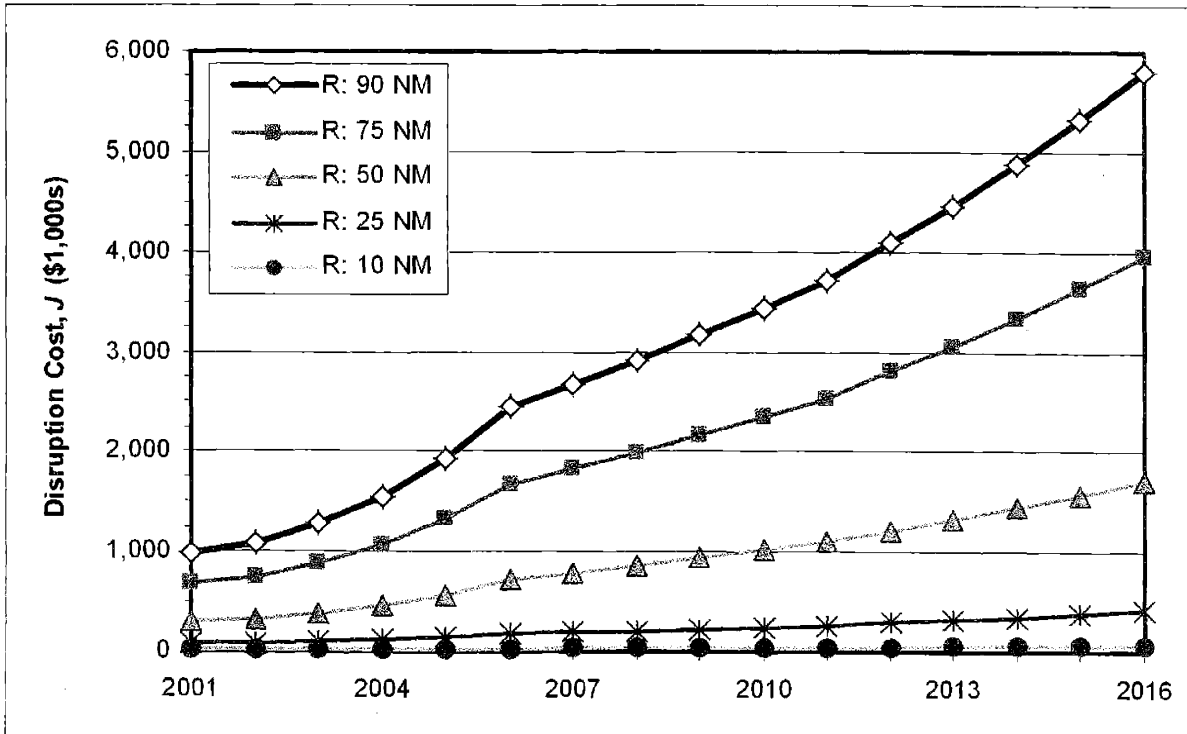


Figure 4.15 Scenario IV: Revolutionary RLVs With Reduced SUA/PZ Size

The effects related to  $\rho$ ,  $R$ , and  $T$  can each be observed in these scenarios. First, in Figures 4.12 and 4.14, the only difference between the top two curves is coordinating launch schedules to reduce  $\rho$ . This immediately decreases the cost by about a factor of 2 (as be expected from  $\rho$  being a simple factor in the ACM) – a significant benefit. The progressively lower curves in these same figures illustrate that the effects of decreasing  $T$  are less significant. However, in Figures 4.13 and 4.15 it is clear that each reduction in  $R$  (transition to a lower curve) significantly decreases the cost. The values of  $J$  for the lowest two cases (smallest  $R$  values) of Scenarios II and IV are well below those of Scenarios I and III (the two smallest  $T$  values with coordinated scheduling), respectively. By 2016 the difference is an order of magnitude in three of these four cases. Therefore it is clear that reducing  $R$  alone would more effectively control  $J$  than reducing  $T$  and  $\rho$  together.

The effects of a high-efficiency RLV dramatically increasing  $E$  are also noteworthy. The largest cases of Scenarios III and IV indicate that if no changes are made, RLV-induced growth would result in three times the disruption costs by 2016 as would nominal growth (Scenarios I and II). This indicates that efficient RLV operations could multiply disruption costs significantly, but that the final cost would still be very small in comparison with other aerospace operations costs. Finally, these scenarios illustrate the potential benefits of more tactical traffic management: in order of decreasing effect, reducing  $R$ , coordinating events to reduce  $\rho$ , or reducing  $T$  could all be used to mitigate disruption cost. In fact, the smaller cases of Scenarios III and IV show that  $J$  could be kept below current levels even with revolutionary RLVs. Combining these measures would be even more effective.

#### 4.4 Implications of the Technical Results

The three principal conclusions of the technical analysis of efficiency are as follows:

- The total disruption cost is sensitive to at least five critical factors, and as various circumstances could result in each of these varying over different ranges, the overall cost is subject to great uncertainty (possibly as much as four orders of magnitude).
- The total annual disruption cost can be expected to rise with increased air traffic or space transportation, but in absolute terms it is expected to remain small (certainly less than \$10 million per year). Nevertheless, several critical factors offer possibilities for mitigating this cost through more tactical aerospace traffic management.
- By far the most critical factor to efficiency is the size of the restricted airspace – this factor alone could multiply or reduce the disruption cost by orders of magnitude. Consequently, any policy decisions related to the disruption cost must first address this factor. (However, safety and other issues must also be considered; see Chapter 5.)



This concludes the focused technical analysis. The next chapter combines these results with policy considerations in order to formulate viable recommendations. Among other things, this involves re-examining the key issues and addressing important tradeoffs, with the goal of applying all available information to make the best possible decisions.

## Chapter 5: Policy Analysis

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This chapter incorporates the findings of the previous chapters along with additional decision issues, stakeholder positions, and political considerations in a comprehensive policy analysis intended to formulate realistic and practical recommendations.

### 5.1 Introduction

The decision originally identified as the impetus for this analysis concerned whether air and space traffic operations should be separated strategically or tactically, other things equal, in order to minimize the total annual disruption cost ( $J$ ) imposed on airspace users. The results of the technical analysis clearly resolved this: tactical separation offers the possibility of enormous reductions in  $J$  as compared with strategic separation. This is certainly desirable, all other things being equal. A critical follow-up point, however, is that the “other things” are highly unlikely to remain equal if something changes. Indeed, the so-called *law of unintended consequences* (often stated “you can’t change just one thing”) is especially germane to CLIOS.\*

This is essential. The technical analysis has provided valuable information about efficiency and its sensitivity to various factors, but without other considerations this can only lead to naïve policy recommendations: simply adjust all factors to reduce  $J$  to the greatest extent possible. The obvious problem with this is that no reasons for doing otherwise have been taken into account. But what exactly should be included, and how?

Many procedures for conducting policy analysis have been recommended, but as yet no method has been generally accepted as “best.” Part of the explanation for this may be that the notion of *policy analysis* is ill-defined, in some cases referring to evaluation and comparison of predefined options, in others to formulation of new options in response to a problem, and in yet others to development of a strategy for implementing a selected option. Most appropriate here is a combination of the first two interpretations (which is not unusual; all three can be involved). Another source of disagreement is philosophical, since decision frameworks range from strict rationality to political accommodation.† But without getting into such details, most recommended procedures do have five basic steps in common.<sup>32, 45</sup>

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\* This is usually ascribed to environmentalist Barry Commoner, whose First Law of Ecology (1971) is “Everything is connected to everything else.”<sup>43</sup> Versions of this maxim quickly spread, and are now ubiquitous.

† Deborah Stone offers an excellent description of these extremes, which she labels the *rational-analytic* and *polis* models of decision analysis, in her new book *Policy Paradox*.<sup>44</sup>

1. Define the problem
2. Lay out the options
3. Identify the valuation criteria
4. Assess the outcomes
5. Make a decision

(Note: if step 5 is to be followed by implementation, it is also advisable to follow-up with monitoring and/or feedback. However, these were not included in the list above because they are outside the bounds of this analysis. The appropriate steps for a given policy analysis depend upon the scope and goals involved.)

The integrated engineering/policy analysis approach developed in Chapter 2 for this study is fully compatible with this general procedure for policy analysis. In fact, the analyses so far basically amount to an iteration of the procedure with a narrow, technical focus:

1. The problem was defined as the current policy forcing space transportation operations to disrupt air traffic (or vice-versa), imposing some disruption cost.
2. A range of policy options was identified, from strategic to tactical separation – these were primarily defined in terms of restricted airspace volume ( $S$ ) and duration ( $T$ ), but the sensitivity of the cost to other potentially major factors was also investigated.
3. The only valuation criterion was efficiency – or more accurately, inefficiency – as represented by the total annual disruption cost ( $J$ ).
4. The findings were that adjusting any factor except relative velocity ( $V$ ) from strategic to tactical values decreases  $J$ , which was found to be by far the most sensitive to  $S$ .
5. The logical decision would be to adopt a traffic management policy involving tactical definition of at least  $S$ , if not all of the factors, to maximize efficiency.

Even though the conclusions were foreseeable, this procedure was useful because it produced quantitative approximations for three key values:

- the size of  $J$  today (around \$1,000,000 – comparatively insignificant)
- the expected growth of  $J$  with traffic density and RLV operations
- the considerable power of policy changes to control  $J$

This information could significantly assist policy-makers in assessing the costs and benefits of various actions associated with this problem, either at present or under other conditions that may be expected to develop. As noted above, however, this is not sufficient to lead to realistic policy recommendations.

Consequently, it is appropriate at this point is to return to Step 1 and conduct a modified policy analysis. This time the intent is a high-level analysis, taking into account as many important dimensions of the problem as possible: safety, efficiency, equity, service, stakeholder positions, issue importance, consensus, and barriers to implementation. As a result, the emphasis will be qualitative – a contrast to the previous focus, but one that should suggest no reduction in value. Many policy considerations, such as stakeholder positions, are almost exclusively subject to qualitative analysis, yet are of great value for identifying the few proposals (if any) that could realistically be implemented. This is exactly the kind of information the following analysis is intended to gain.

## **5.2 Comprehensive Analysis**

As explained above, this section presents a comprehensive analysis of the general policy decision, distinguished from the previous analyses by its attempt to include all major factors, both technical and policy-related, and by being predominantly qualitative rather than quantitative in nature. The basic procedure follows the five steps described in section 5.1.

### **5.2.1 Problem Definition**

The main problem definition remains the same as identified previously: the current aerospace traffic management policy forces air and space transportation to disrupt each other, involving a cost that is expected to rise with growth in either mode of operations. The changes that will differentiate this analysis begin to appear in the next step – describing the policy options.

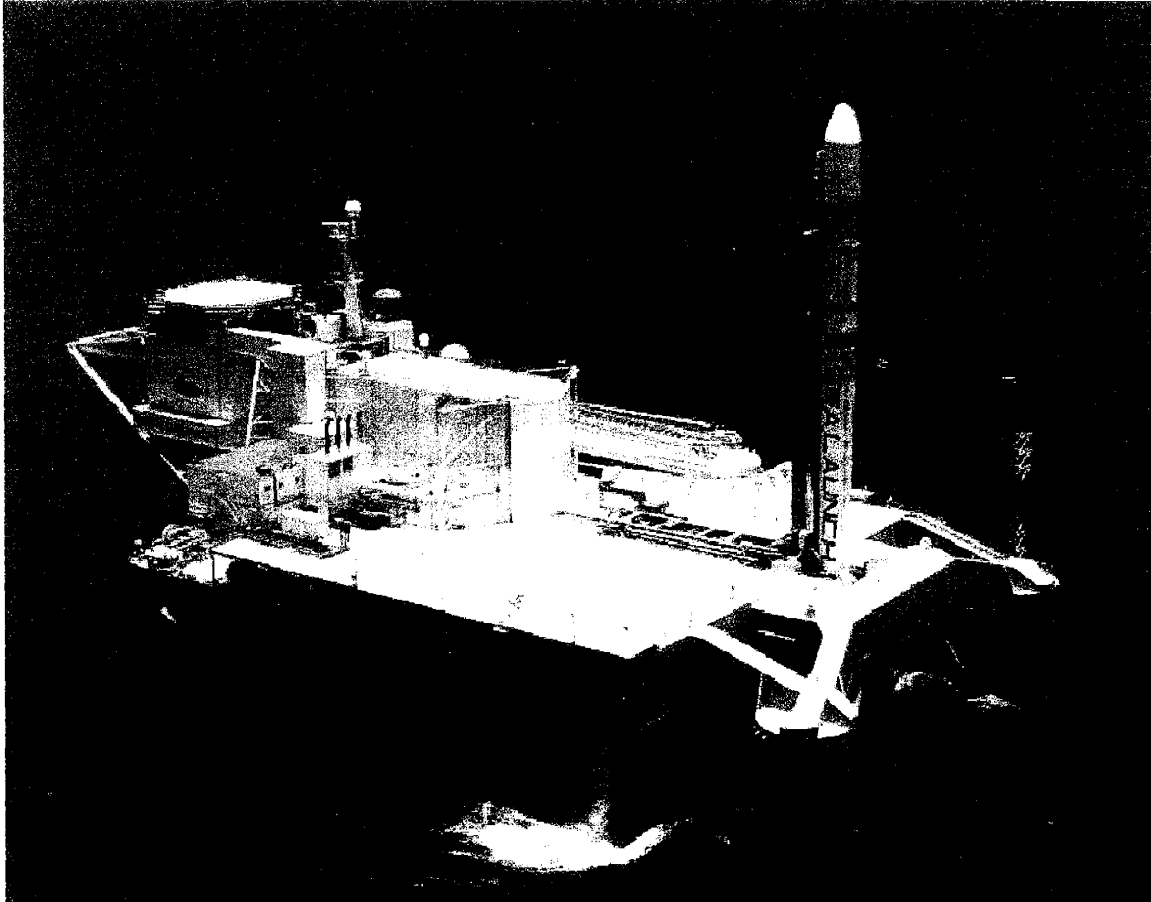
### **5.2.2 Policy Options**

Among the main findings of the technical analysis were that  $J$  is heavily dependent on the size of the restricted airspace ( $S$ ), and is also sensitive to the restricted duration ( $T$ ) and the background air traffic density ( $\rho$ ).<sup>\*</sup> Accordingly, the first three policy options advocate reducing each of these (i.e., reducing  $S$  and  $T$  directly, and reducing  $\rho$  indirectly through coordinated scheduling, as in Scenarios I and III in Chapter 4). Note that the options need not be exclusive; a combination of several in moderation could be at least as effective as the strict implementation of one, and might be more acceptable to certain stakeholders.

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<sup>\*</sup>  $J$  was also affected by the annual space transportation events ( $E$ ) and the Alert Zone range ( $Z$ ), but as these are less directly controllable and  $J$  is less sensitive to them, they are not included as primary policy options.

There is also one other option. Recently, an expendable launch vehicle (ELV) operating from a mobile platform in a remote location has been developed. This enables a new solution: if disruption costs begin to rise, shift space operations to airspace that air traffic is not using. Figure 5.1 depicts Sea Launch, the first system to demonstrate this capability.



*Figure 5.1 The Sea Launch System, at the Equator in the Pacific Ocean* <sup>46</sup>

All told, this amounts to four principal options identified for Step 2 of the policy analysis:

- reduce the size of the restricted airspace ( $S$ )
- reduce the duration for which the airspace is restricted ( $T$ )
- coordinate space transportation events with air traffic to reduce traffic density ( $\rho$ )
- shift operations to a remote location to simultaneously reduce  $S$ ,  $T$ , and  $\rho$  to zero

### **5.2.3 Valuation Criteria**

The key issues identified in transportation policy decisions of safety, efficiency, equity, and service must all be considered. In addition, the overall ease of implementation of each option will be assessed through consideration of various policy factors. Critical to all such assessments are the major stakeholders and safety, so a section is devoted to each before continuing the analysis.

### **5.2.4 Major Stakeholders**

While it is possible to generate recommendations on the basis of engineering or economic analysis alone, this would run the risk of omitting one of the most important factors affecting actual events: the stakeholders. These individuals and organizations are interested in policy decisions because they have something to gain and/or lose, so logically they may take action to support or oppose any given proposition. Accordingly, it is usually crucial to consider the positions and powers of major stakeholders when formulating recommendations.

In general, there are four broad categories of stakeholders to consider in aerospace transportation policy decisions. These are each described below, with notes about salient members for this issue:

- Operators – those who operate transportation systems, including *carriers*, primarily flying to transport passengers and/or cargo between locations, and other operators flying for various reasons (pleasure, research, military operations, etc.). Of note in this case are commercial air carriers, general aviation (GA), and the operators of space transportation systems. (This last group could conceivably be separated into commercial and governmental elements, but these are currently almost identical.)
- Consumers – those who depend on carriers for transportation services. This includes air passengers and those concerned with air or space cargo transportation, but in this case their interests are not sufficiently distinct from those of the carriers to warrant separate consideration (both want safe and efficient operations).
- System Managers – those in charge of setting policies and directing or overseeing operations. In this case this includes a variety of government agencies: the Department of Defense (DOD), the National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), and air traffic controllers (also part of the FAA, but these are operational managers, different from policy-makers).
- The Public – all others concerned with aspects of the policy decision, but not directly involved as operators, consumers, or system managers. This often includes special

interest groups (environmental, humanitarian, etc.), which can be significant players in the policy arena. This case, however, primarily concerns “internal” stakeholders (above). The only important public group to consider is Congress. (The general public could also be considered, but this is not likely to be a popular concern.)

In total, this amounts to eight major stakeholder groups that may be important for aerospace traffic management policy decisions. The main interests and general political influence of each are briefly characterized below.

**Commercial air carriers**, or “airlines” for short, simply wish to stay in business (profitably). This is no simple matter because commercial air transportation is, by any measure, a highly competitive industry. Despite decades of growth in operations, airlines have faced extremely low profit margins since deregulation (1978), and since the terrorist attacks of September 2001 expect significant losses through at least 2003.<sup>5</sup> Politically, however, airlines are very powerful (collectively), and their policy goals are straightforward: cut costs and increase freedom. The latter has recently begun to redefine their relationship with regulators. In everything from daily traffic management to long-term policy-making, the FAA has moved from unilateral direction to collaborative decision-making. Perhaps the ultimate goal in this vein is Free Flight, in which commercial pilots will be able to fly directly from origin to destination (or re-route however they see fit). While this is still an unclear future prospect, progress toward it has become an official goal.

**General aviation (GA)** includes all aspects of aviation except commercial and military. Although not as high-profile as those in general, it is nearly as important: GA operations account for most aircraft movements (i.e., flights) worldwide, and about half of all air traffic in the US National Airspace System (NAS) at any given time. Politically, they are known for a well-organized lobby, aggressive (and often successful) in defending the freedom of GA pilots to fly throughout the NAS. In the wake of the terrorist attacks, however, GA operations were heavily restricted in several areas for reasons of security. Although they have since regained access to most of this airspace, the unambiguous policy at present is to immediately and indefinitely prioritize security over GA concerns – a development which may well have wider implications for this policy analysis.

**Space transportation system operators**, or “spacelines” for short, have been historically governmental, and although commercial space transportation is growing into an industry of respectable size, in the US it involves the same companies (and mostly even the same vehicles), so a distinction is unnecessary. Space transportation service is rarely considered important – even commercial space ventures typically view launch service as a secondary concern – with the notable exception that the capability is a military and governmental priority. But these are subsets of other agencies (mainly DOD), not different stakeholders.

The political power of spacelines is difficult to judge, because they currently operate infrequently and gain access to Special Use Airspace (SUA) upon request. In the absence of new opportunities in space or significantly more efficient launch vehicles, they are likely to continue operating at low rates from a few locations and remain “minor players” in policy circles. A potentially noteworthy consideration, however, is the fact that the major companies providing space transportation services (Boeing, Lockheed-Martin) are also the major government contractors for aerospace systems. Hence they could have some political clout, should a need arise.

The **Department of Defense (DOD)** is one of the most important stakeholders in any aspect of this analysis, for several reasons. First, with all matters of national security as its purview, the DOD basically has the ability to trump any concerns, except possibly safety, of all other stakeholders. Second, the DOD includes the Air Force, which essentially “owns” both the Eastern and Western US Space Launch Ranges and – most importantly for this study – all of the SUA associated with space transportation. (Technically, a few commercial spaceports do exist, but except for one being developed in Kodiak, AK, all are collocated with Air Force facilities and therefore subject to DOD control.<sup>47</sup>) Finally, the DOD is the major consumer of space transportation services (at present and every year historically except for 1997). All told, this amounts to the DOD having great power in this area, but it is limited. Congress sets DOD budgets, and is perennially leery of costs that cannot be sufficiently justified by credible military threats. Thus the privatization of various aspects of launch ranges has been seriously considered, and even shared control of SUA is conceivable.

The **National Aeronautics and Space Administration (NASA)** is probably the next most important stakeholder in this policy decision, after the DOD. As the civil space authority, NASA is basically in charge of all nonmilitary space operations, including space transportation. Since the development of the Space Shuttle, with its enormous schedule and budgetary pressures, NASA has generally had little involvement with other space transportation systems. But in an effort to control costs, the new Administrator recently announced that the Shuttle will fly only four missions per year. Since this is barely sufficient to serve the International Space Station alone, this policy necessarily means NASA will begin using ELVs again for other missions. If so, it can be expected to have almost as much power in space transportation policy as the DOD, except without the security mandate.

The **Federal Aviation Administration (FAA)** is primarily a stakeholder because it controls the NAS, which includes the airspace through which all space transportation operations must pass at least on ascent (possibly again if they return) and within which most aviation operates exclusively. As such it directly controls most aviation, and has historically dealt with space transportation through SUA, which is either available for general use or restricted to all but space operations, as explained earlier. Should a tactical aerospace traffic management policy



be developed, however, this would probably change, and the FAA would become integral to all aerospace operations in the NAS. Secondary FAA involvement derives from its Office of the Associate Administrator for Commercial Space Transportation (AST). AST performs some traditional FAA functions related to licensing, safety, and the development of standards, but is also planning for future operations. In this last aspect the FAA is proactively considering RLVs and options for aerospace traffic management, and is responsible for this study. Consequently, the FAA could conceivably expand its domain as aerospace operations develop, potentially one day controlling all flight not just up to 60,000 feet, but to orbit.

**Air traffic controllers**, or “controllers” for short, are technically part of the FAA, but it is often reasonable to consider them as a separate stakeholder; in fact, they are relatively famous for developing their own opinions and acting autonomously. This follows directly from their duties and environment. While the “administration” part of the FAA is concerned with licensing and policy-making, controllers are concerned with managing air traffic. Theirs is a high-pressure environment, in which they are simultaneously directed to maintain safety at all costs and pressured to improve efficiency. In tactical conflict resolution, these are directly opposing goals: safety is improved by increasing the separation between aircraft; efficiency is increased by “pushing more tin” through the airspace. As a result, controllers are highly skilled practitioners who, as a group, tend to strenuously resist most changes. From their point of view, any new procedures or technologies require retraining and an adjustment period during which safety and efficiency are both lower. They have developed a fairly strong labor union. As a result of this, the importance of their function, and their position as the people who directly implement (or resist) changes in air traffic management policy, they can be important to consider in policy planning.

Finally, **Congress** is the legislative branch of the US government and also a special class of the public, specifically designated to represent the populace in policy-making. Both houses of Congress are divided into numerous committees and subcommittees specializing in various functions. Relevant to this study in the Senate is the Commerce, Science, and Transportation Committee, which includes both an Aviation Subcommittee and a Science, Technology, and Space Subcommittee. In the House, however, the Aviation Subcommittee is under Transportation and Infrastructure, while the Space and Aeronautics Subcommittee is under Science. These subcommittees are deeply involved with both air and space operations management. With respect to aviation especially, the concerned subcommittees are sometimes accused of micro-management.<sup>48</sup> Consequently, the members of Congress represent a complex amalgam of legislators, planners, and budget-controllers, ranging greatly in personal knowledge and interest in aerospace policy. Most such matters are left to the agencies primarily responsible for them (FAA, NASA, DOD), but Congress exercises careful oversight, and when it does become involved obviously exercises tremendous power.

This completes an introduction to the major stakeholders. The next section focuses on safety before continuing with the comprehensive policy analysis.

### 5.2.5 Safety

The reason for creating SUA in the first place was that expendable launch vehicles (ELVs) are essentially modified missiles, loaded with high-explosive propellant and traveling at very high speeds. Even if all goes smoothly, such vehicles drop stages during ascent, making it necessary to restrict the area both so unrelated aircraft do not stray too close to the launch vehicle, and so no aircraft (or maritime vessels) are endangered as the stages fall back to Earth. Should an anomaly develop, however, the range safety officer may have to abort the mission and destroy the launch vehicle. In such an extreme case it becomes important that none of the debris cause harm, so this also factors into risk management.

#### Regulated Standards

The primary safety regulations governing operations at the Eastern and Western Ranges are codified in EWR 127-1, a joint publication of the Air Force 45<sup>th</sup> and 30<sup>th</sup> Space Wings (of Cape Canaveral Air Station, FL, and Vandenberg Air Force Base, CA, respectively).<sup>49</sup> This document defines two principal safety standards:

- collective risk criterion:  $30 \times 10^{-6}$
- individual risk criterion:  $1 \times 10^{-6}$

The *collective* risk criterion of  $30 \times 10^{-6}$  indicates that the collective risk to the general public must be expected casualty rate no higher than 30 in one million, or 1 in 33,333 launches. Since there are typically about 33 launches per year, this means the risk to the public is estimated at a fatality occurring once in 1,000 years. The *individual* risk criterion is  $1 \times 10^{-6}$  (or  $1 \times 10^{-5}$  for mission-essential personnel), or one in one million. This standard applies to the maximum acceptable risk to any individual in a specific location, and is used in modified forms for individual aircraft or marine vessels.<sup>50</sup>

These range safety standards were recently reviewed by the Committee on Space Launch Range Safety of the National Research Council. This committee found that the collective and individual risk criteria were consistent with other regulated risks, but that the individual risk criterion was interpreted differently for aircraft at the Eastern and Western Ranges. The committee's recommendations were that EWR 127-1 should be modified to specify an aircraft hit probability limit of  $1 \times 10^{-6}$ , calculated to include even very small debris (as little as 2 grams), and that this should be standardized for both ranges.<sup>50</sup>

## Collision Analysis

While modeling the debris associated with launch vehicle destruction is beyond the scope of this analysis, it is possible to modify the Airspace Conflict Model (ACM) to estimate the probability of a collision or near-collision. This is done by using the ACM to predict the number of conflicts associated with restricting the airspace taken up by a single aircraft for the duration it takes a launch vehicle to transit that space. The (very small) result is set equal to the mean of a Poisson statistical distribution, appropriate for infrequent events, which enables calculation of the probability of zero conflicts associated with that process. This is the complement of the desired probability, so it is simply subtracted from one to determine the probability of one or more (i.e., any) collisions.

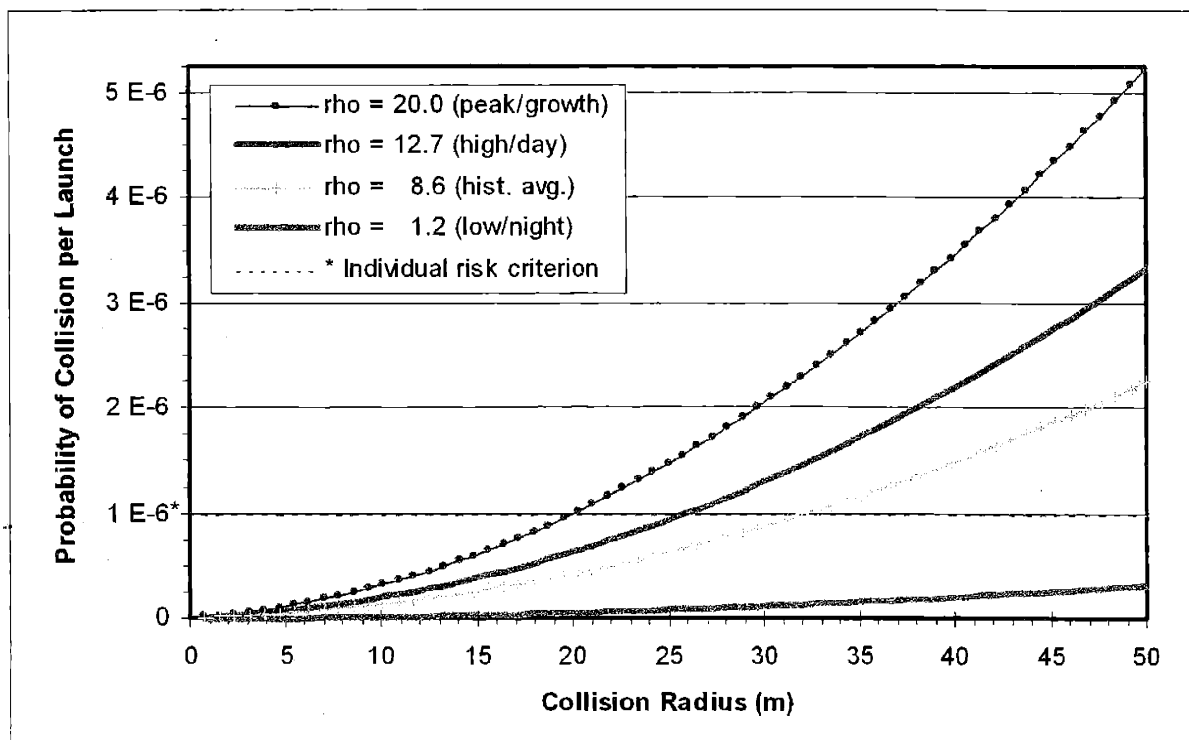
To apply this method a collision airspace must be defined. For analytical convenience this volume can be cylindrical, which enables it to be defined in terms of height and radius. A height of about 16 m (52 ft) and a radius of about 30 m (98 ft) will accommodate most commercial aircraft. This can be modeled in the ACM with a restricted duration of 0.048 seconds, which corresponds to a conservative estimate of the time it takes a launch vehicle to pass through the spatial region. (Even a heavy launch vehicle like a Delta IV accelerates to Mach 1 by 30,000 ft, so this speed can be used to convert distance into time: at Mach 1 it takes only 0.048 seconds to travel 16 m.) During 0.048 seconds in the altitude vicinity of commercial air traffic, most launch vehicles can be expected to ascend farther than 16 m, which is the reason a more conservative height was not selected.

Similarly, the appropriate radius of the collision airspace depends on the local air traffic. A typical range would be from around 15 m (49 ft) for a small aircraft like a Cessna Citation, to about 35 m (115 ft) for a Boeing 747. A smaller radius may be appropriate for general aviation (GA), or a larger radius could be used to model "near-misses." 30 m is suggested as a reasonable average for most commercial air traffic, but rather than fixing this parameter, a range from 0 to 50 m was investigated and plotted in Figure 5.2.

Using a duration of 0.048 seconds and a radius of 30 m in the procedure described above estimates the probability of a large ELV colliding with a fairly large aircraft on the basis of traffic density, geometry, and statistics. Since many launch vehicles accelerate more rapidly and many aircraft present smaller targets, this may be rather conservative for the probability of a direct collision. Then again, given that a near miss could still be extremely hazardous, this might not be conservative enough.

Four curves are plotted in Figure 5.2 to illustrate the sensitivity of collision risk to traffic density. The traffic densities of 1.2 and 12.7 (aircraft per 10,000 NM<sup>2</sup>) correspond to the recent averages for nighttime lows and daytime highs from Chapter 3. The value of 8.6 was

the historical traffic density estimated for Space Shuttle launches in Chapter 4. The final value of 20.0 represents current peak traffic densities, and also indicates potential effects of further traffic growth in the future.



**Figure 5.2 Probability of Collision or Near-Collision Without SUA**

The data plotted in Figure 5.2 suggest that if no precautions whatsoever were taken and ELVs were simply launched through air traffic at random, the probability of a direct collision would be very low. As shown by the top curve, even the largest aircraft (radius under 49 m) flying at today's peak en-route traffic density (~20 aircraft per 10,000 NM<sup>2</sup>) would create a collision probability of only  $5 \times 10^{-6}$ . At 33 launches per year, it would take an average of 6,000 years for one collision! The collective risk criterion of  $30 \times 10^{-6}$  is not directly shown on this plot, but it can still be considered, as discussed below. The individual risk criterion of  $1 \times 10^{-6}$  is depicted. For a collision radius of 30 m, only a traffic density at or below 9.8 aircraft per 10,000 NM<sup>2</sup> results in theoretically acceptable risks. This exceeds the estimated historical average, which would suggest that SUA has been technically unnecessary all of these years.

These results may be somewhat misleading, however, because most aircraft carry passengers. If a typical commercial flight carries 100 people, the severity of a collision is 100 times higher. This means the probability must be 100 times lower for the risk to be equivalent. The

collective risk criterion therefore requires a maximum probability of  $3 \times 10^{-7}$ . For a collision radius of 30 m, the maximum acceptable traffic density falls to only 2.94. Since both probability and severity determine risk, severe consequences can make a risk unacceptable even if the probability of the dangerous event is extremely low.

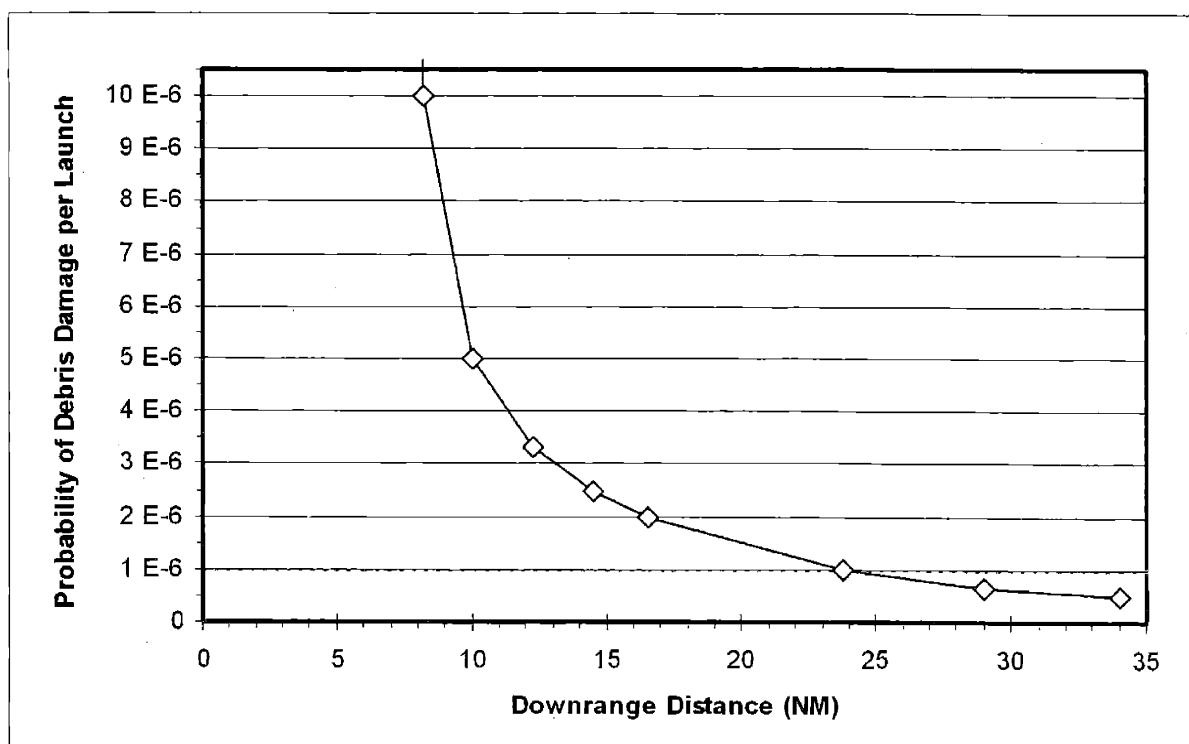
These results suggest that restricting a large region of SUA may not always be necessary for preventing direct ELV-aircraft collisions. This relates to the colloquial “big sky” theory, which posits that the amount of airspace is so large, compared with the number and size of vehicles traveling through it, that collisions are statistically unlikely.<sup>51</sup> Yet as traffic density rises, the risks become significant and require SUA. This indicates when SUA of various sizes may be needed for direct collision risk management, but provides little insight into SUA effects on *overall risk*, in which direct collision is but one factor. Other factors include position uncertainty coupled with very high speeds, the truly acceptable “near miss” range in light of rocket wake and exhaust concerns, and especially the debris ballistics in the event of catastrophic failure. These could be quite important, and require detailed safety analysis.

#### Detailed Safety Analysis

It has been shown that if smaller regions of airspace can be restricted around launch events, disruption costs will fall (Figure 4.1). Logically, however, reducing SUA size should also increase risks. Therefore a complete safety analysis should go on to investigate the changes in collision risk with SUA radius, and the tradeoffs between safety and efficiency. Unfortunately, this requires much more information. Note that the collision radius above is very different from the SUA radius investigated in previous chapters. The collision radius models only a direct collision. Inside it destruction is assumed to be certain, while the risks beyond are unclear. SUA is conceptually opposite, bounding an area such the outside should be sufficiently safe from all launch-related risks, while interior risks are unclear. These are each extremes; a full risk analysis must assess the risk gradients between them.

This is not attempted here. The principal motivation for this research was the concern that using SUA to separate air and space traffic might sometimes restrict larger temporal and spatial buffers than are truly required for safety, and that in the future this might become significantly costly and/or restrictive. Accordingly, this analysis has first looked into the costs involved with restricting this airspace, and found them to be low. Without pressing economic reasons, changes in the direction of decreasing safety are unnecessary. However, if one day those economic reasons do arise, then a rigorous analysis of the safety impacts of restricting less airspace will be required. If at that time catastrophic failure or destructive abort is still a significant concern, it will likely dominate risk management decisions, so that safety analysis may require detailed debris modeling and probabilistic damage assessment.

A brief example is presented below to illustrate the value of such a complete analysis. The actual risks posed to aircraft by debris from launch vehicle failure modes were not available, so Air Force downrange debris hit-probability contours for boat hits were adapted to estimate the probability of hitting an aircraft with debris of similar size.<sup>50</sup> This relies on the assumption that an aircraft is approximately the same size as a boat, and that debris of similar size would cause an accident. Assuming that the SUA extended a given distance downrange, the hit probability for an aircraft on the downrange edge of the SUA is given by Figure 5.3. In fact, the actual probabilities of an accident would be higher because aircraft can typically be threatened by smaller debris than boats, but this was not included in the boat-hit computations. An additional consideration, however, is that at locations not directly downrange the probabilities would likely be significantly lower than shown by this curve.

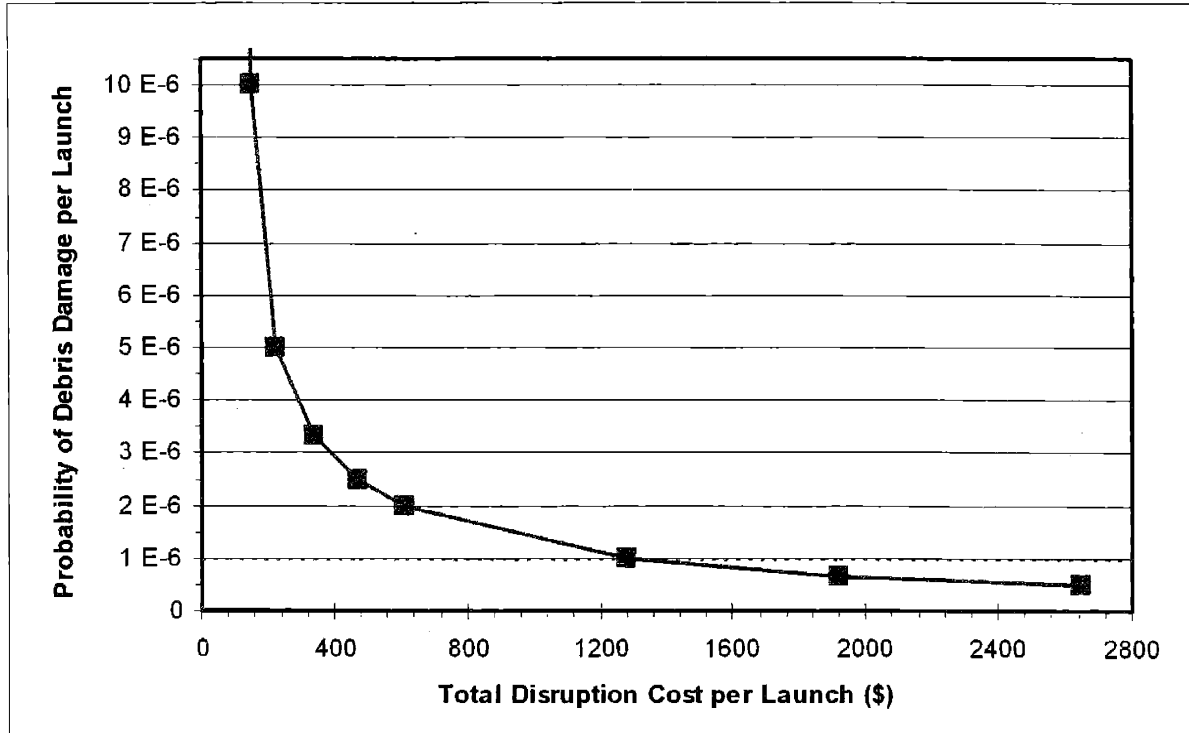


*Figure 5.3 Probability of Debris Damage vs. Downrange Distance*

This analysis suggests that the minimum downrange SUA size to satisfy the individual risk criterion is approximately 24 NM. To satisfy the collective risk criterion for aircraft having an average of 100 passengers, however, the SUA would have to be about 40 NM.

This formulation can be combined with the assessment of disruption cost as a function of SUA radius in Chapter 4 to investigate the tradeoff between risk and cost. This is illustrated in Figure 5.4, which was created by plotting the probability data in Figure 5.3 against the

disruption cost associated with restricting an SUA of each radius. The other parameters underlying these calculations are the historical average traffic density (8.59), the current average duration of 180 minutes, and the typical values for traffic speed (450 knots) and Alert Zone range (5 times the radius).



*Figure 5.4 Tradeoff: Probability of Debris Damage vs. Disruption Cost*

Figure 5.4 shows the expected cost due to deviation around the SUA for a given hit probability from Figure 5.3. The current KSC SUA extends at least 180 NM downrange (but corresponds an SUA radius of only 90 NM; the launch proceeds east from near the western edge, not from the center), which this analysis indicates would correspond to a debris hit risk of approximately  $5 \times 10^{-9}$  and cost of nearly \$20,000 per launch.

Figure 5.4 illustrates the expected tradeoff between cost and risk: restricting a larger area increases safety but also costs more. Note that this is only hypothetical – adapted from boat-hit data – but it appears that a small increase in cost initially buys a large gain in safety, while further expenditures result in diminishing marginal safety gains. (Were this the actual aircraft analysis, it might be better analyzed on a log plot, to facilitate comparing orders of magnitude.) This is exactly the kind of information required to make appropriate decisions about SUA size in order to balance the competing interests of safety and efficiency.

## Safety Conclusions

In this study, the cost-efficiency findings have obviated the need for detailed safety analysis in the short term. In other words, it is not too expensive to be safety-conservative for the time being. A crude collision analysis suggests that the current SUA may have been designed as much for operational simplicity or political justification of safety as for real collision risk management, but preliminary analysis of comprehensive risks, based on boat-hit data, indicates that satisfying the collective risk criterion when dealing with aircraft carrying many passengers could quickly require large downrange distances. Accordingly, more detailed analysis of aircraft debris-hit risks to investigate the minimum areas meeting safety standards will be required if it at some future point it does become important to reduce SUA size.

This concludes a quick investigation of safety, both in terms of the current regulations and their apparent relation to actual operations. The next section continues the comprehensive policy analysis by assessing each of the four options introduced in section 5.2.2.

### ***5.2.6 Policy Assessment***

**The first policy option** is to reduce the size of the restricted airspace (*S*), the efficiency advantages associated with which were found to be enormous in the technical analysis. The most immediate concerns with this suggestion relate to safety. The preliminary analyses above indicate that the probability of a direct collision is small, but the risks may be significant. However, the actual debris risk to aircraft upon launch vehicle destruction have not been examined, for want of applicable data. This would be an excellent subject for future analysis, should this policy option be deemed worthy of additional consideration.

In further consideration of SUA and safety, two important points can be made. First, current SUA, such as shown in Figure 3.4 for the Kennedy Space Center (KSC), is designed to support operations involving various trajectories. This suggests that only subsections of the SUA may be technically necessary for specific launches, in which case perhaps smaller areas could be restricted without compromising safety. For example, perhaps "space transition corridors" of a given width could be defined along the specific trajectory of a launch/landing operation. However, it should be noted that as long as these corridors run mainly east-west, and traffic predominantly travels north-south, this may not substantially reduce impacts.

Second, alternative launch vehicle concepts may substantially affect the risk/safety calculations. This refers primarily to new RLV concepts, but could certainly apply to the existing Pegasus launch vehicle. Its first stage is a conventional L-1011 aircraft, which does not fly at very high speeds and, until the moment of launch vehicle separation, involves



whole-safe-return abort modes. Hence it appears that this vehicle could already qualify for reduced  $S$  without compromising safety. Others may similarly merit reduced requirements.

The other major issue with this policy option concerns acceptability. The military is very protective of its airspace, feeling it has already given up all it can afford to yield, and has resisted related suggestions that it free up more airspace for air traffic in Nevada. Consequently, the DOD naturally should be expected to oppose a suggestion to reduce its airspace around the space launch ranges. (Note: a potential compromise might be reducing the components of SUA that are activated for some launches, while not technically eliminating the SUA designation of any airspace, so DOD would still have it when needed.) Events since the terrorist attacks of September 2001 heavily reinforce this. The author was recently informed by a traffic manager at the Miami Air Route Traffic Control Center that for security reasons the military was more rigidly protecting its airspace than ever, and that controllers were complying by diverting air traffic well clear of SUA boundaries.

This is certainly understandable on security grounds. Aside from the direct risk to people and facilities on the ranges, the US can hardly afford the political risk of an attack at KSC or Vandenberg. A successful attack on the Vehicle Assembly Building or especially a Space Shuttle orbiter would create the appearance of the nation being unable to protect even highly valuable resources, despite its vaunted technology.

In light of these developments, it may be sensible to abandon this option as politically infeasible for the short term. Considering the potential savings associated with reducing  $S$ , however, it certainly is worth reconsidering if disruption costs become burdensome in the future, for example if both air traffic levels and annual space transportation events increase. But at this time, it is probably only feasible as an exception for special cases, such as the Pegasus launch vehicle, rather than as a general policy adaptation.

**The second policy option** is to reduce the duration for which the airspace is restricted ( $T$ ). The technical analysis found the efficiency advantages associated with this to be significant, though not as much as with the previous policy option. In this case safety is again the most immediate countervailing consideration. The details of the current policy setting the timing of SUA activation, or "launch-specific restrictions," are unfortunately not available to the public (ostensibly for security reasons). Accordingly it is necessary to fall back on reports of SUA restriction roughly three hours before a launch.<sup>52</sup> Even more than spatial restrictions, this is clearly not directly driven by collision-related safety concerns, since the launch vehicle actually transits the NAS in under two minutes. Instead, the long temporal buffer preceding the event is designed to give FAA and launch range officials time to ensure that all air and surface traffic is in fact out of the area.

Ignoring surface traffic since it is outside the scope of this analysis, the air traffic of concern is almost exclusively GA. Aircraft operating under Instrument Flight Rules are under positive control, with their locations precisely tracked by radar, so nowhere near such a large buffer is required for them. GA flights operating under Visual Flight Rules, fly autonomously within uncontrolled (Class G) airspace. They are not necessarily precisely tracked nor in contact with any controllers. Consequently, the long pre-launch buffer serves a dual purpose for GA: hopefully it enables news of the SUA restriction to reach the pilot (in the form of a Notice to Airmen or preflight briefing) before (s)he takes off, and even if not, it gives patrol aircraft around the SUA time to spot the intruder and warn/escort it away.<sup>53</sup>

This latter consideration, however, suggests that the current *T* is not so much a matter of safety as of operational convenience. If this is the case, the proposal to reduce *T* may be fairly reasonable. Unfortunately, the problem of removing GA aircraft from the vicinity is not easily resolved. Many such aircraft are deliberately flying *toward* the launch/landing site, in hopes of getting a good view, and perhaps a few photographs. Some possibilities include requiring all GA flights within a certain distance of the site to identify themselves to controllers, and/or perhaps even requiring all aircraft approaching within a certain distance to be equipped with radar transponders that will ensure their visibility. However, such measures are exactly the sort that the GA lobby would vigorously oppose, claiming that they were (1) unwarranted, (2) violating the freedom of private pilots to fly in the area and enjoy unique sites, and (3) unduly expensive (in the case of the radar transponder). The very fact that such measures have not already been implemented suggests that they might be difficult to enact.

Other than the GA issues, however, there seems to be little controversy surrounding this policy option. This suggests that perhaps it could even be implemented in stages: since commercial flights are both in contact with controllers and precisely tracked, perhaps they can be more tactically rerouted – only re-routed around SUA within the last 20 minutes before an event, for example – while the strategic timing was kept in place for all flights not participating in this “clearly tracked and controlled” program. (Anecdotal evidence suggests that controllers do occasionally make exceptions for some controlled flights today, routing them across part of an SUA rather than all the way around, when the controllers know the high-risk event will not be taking place for some time.)

GA might attempt to challenge such a policy as inequitable, but it is not without precedent. In fact, such “tiered” equipage/clearance regions are already in place around major airports (Class B and C airspace). Moreover, security concerns since September 2001 give such considerations extra merit. So this policy option seems potentially effective and fairly easily implemented, and all things considered much more viable than the first option.

**The third policy option** is to coordinate space transportation events with air traffic to reduce the effective traffic density ( $\rho$ ). The scenarios investigating this in Chapter 4 resulted in a 50% reduction in cost for a relatively modest scheduling effort. This appears to be an excellent option, at least upon initial review, because it would involve absolutely no need to compromise safety (including security) in order in order to improve efficiency.

Instead, the first questions this option raises address how costly or restrictive it would be to actually implement. A brief review of windows for actual launch events indicates a surprising range of launch window sizes, from several hours down to less than five minutes.<sup>42</sup> Hence the important question in this case concerns the costs associated with “moving” these windows. If defined by special orbital mechanics scenarios, they could conceivably be prohibitively costly to move. For example, doing so could mean missing or reducing a gravity-assist, which would mean having to add additional fuel, which could mean having to eliminate the payload (!) in order to still be able to reach orbital velocity. In other words, unless the launch occurs within the defined window, it does not occur. Nor does the tradeoff need to be so extreme; the costs of disrupting air traffic for any given event are only on the order of \$18,000. So if the costs of altering space transportation events is greater than this, the costs of this option would outweigh the benefits.

On the other hand, launch windows for some missions could conceivably be defined for optimal communications intervals or even for convenient access to ground systems (launch pads, etc.). In such cases there might be very low costs associated with adjusting the windows, making this perfectly feasible. This may be worth investigating if this option is otherwise deemed worthy of consideration.

Assuming it is feasible, there may still be a small equity/service issue, but this would not be prohibitive: if altering space transportation schedules to reduce the disruption cost were found to inconvenience the spacelines (more than it inconveniences the airlines to have to circumvent the SUA), it would only be necessary to work out a system of compensation or incentives. But this may be small compared with overall disruption cost that already may have to be distributed fairly, once it has been reduced as far as reasonably possible.

All things considered, there is no reason to expect any of the stakeholders to mount significant political opposition to the third policy option, as it is not likely to involve much hardship for any of them (noting that when it is impractical for the spacelines it will not be considered at all). Furthermore, it would not be difficult to implement if agreed upon, since it would require no technology or infrastructure changes, and only very minor operational changes. Therefore this seems to be a legitimately promising option, and it is definitely worth investigating the primary technical feasibility question about the cost involved in moving launch windows.

Finally, **the fourth policy option** is to shift ELV operations to a remote location where there is little or no air traffic to disrupt. Like the previous option, this offers the advantage of not forcing a tradeoff between safety and efficiency. For Sea Launch specifically, it is conceivable that there could be some concerns related to security, since it is not a wholly-US launch vehicle, but these would probably be minor. But even if the State Department or DOD were to insist upon rigorous security measures that it was impossible to satisfy for some reason with Sea Launch the general option remains viable. Two “workaround” possibilities include either shifting only commercial (non-sensitive) payloads to Sea Launch, or simply developing a purely domestic version for sensitive payloads. (The latter would take a little time but would hardly be infeasible, especially given the significant US involvement in the existing Sea Launch.)

This option should also meet little resistance from stakeholders, except for possibly some dissatisfaction on the part of other spacelines simply because of business lost to a competitor. This would be very unlikely to go as far as direct opposition, however. It would probably amount to little more than a few pleas to DOD and Congress to “save jobs,” or at most stretch to an issue of equity. Ultimately, however, the fact is that space launch has always been a competitive business, so whoever can offer better service temporarily pulls ahead.

There may be other concerns may be related to efficiency and performance. It is probably costly to move an entire launch platform to a remote location for each operation. This may be especially stark in comparison with the Evolved Expendable Launch Vehicles currently being developed, which promise significantly improved efficiency and performance. (However, many launch systems have made bold promises in development that were never fully realized when completed.) There are also design considerations; such systems will be unmanned, and may only support payloads within certain conditions, but this true for any launch system. In addition, Sea Launch specifically is a relatively new system and has experienced one failure in its first seven launches, so reliability may be an issue (although this record is actually better than average for a new ELV). Finally, the time required to ship payloads, launch vehicles, etc. to a remote location may mean this can only support a few launches per year for a while, making this a somewhat limited alternative.

All things considered, however, this option would reduce disruption to zero for all operations it supported without compromising other values, and should involve no significant barriers to implementation, making it an excellent prospect overall.

### 5.3 Policy Recommendations

The primary conclusion of this analysis is that the total annual cost of air traffic disruption due to space launch is currently insignificant (less than \$1 million).

However, if this cost were to increase sufficiently to warrant action, and if a policy decision had to be made immediately, the best recommendation appears to be a combination of several options, some short-term and others that may be implemented over time.

First, the schedules of all upcoming but not imminent launches (say at least six weeks away, but not more than a year off) should be examined. Any that are planned for peak air traffic periods should be reconsidered, assessing the cost/difficulty that would be involved in rescheduling them for off-peak periods. If the launch windows prove relatively flexible, all events (in the same time frame) planned for the transition intervals should also be examined, to see if any can be rescheduled for the minimum air traffic periods.

Second, those operations that cannot be easily rescheduled for off-peak times should be considered for launch from a remote location. Depending on the supply of launch vehicles, payload matching, and orbital requirements, it may not be possible to schedule such operations for a year or so, but this is at least worth looking into.

Finally, the FAA and DOD should investigate the following four possibilities for moving toward more tactical aerospace traffic management to reduce disruption costs:

1. Reduce the duration for which SUA is restricted in general.
2. Unless (1) is feasible and able to be implemented soon, allow controlled aircraft to transit the SUA until a shorter period before actual events, only maintaining the full restricted durations for uncontrolled air traffic.
3. Reduce the SUA requirements for the Pegasus and similarly "safe" vehicles, as long as any actual rocket stages are launched over water in remote areas.
4. Reduce the size of the SUA restricted for at least some launches, such as those involving particular trajectories.

Depending on how soon the various elements could be implemented, and to what extent, these recommendations could significantly reduce the disruption cost even in the short term (within two years), and should be able to keep it below any relevant maximum through the medium term (less than twenty years) even if air traffic continues to grow and efficient new RLVs are developed that result in substantial growth in space transportation events.

## Chapter 6: Conclusion

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This chapter concludes the thesis with a synopsis of highlights from previous chapters, a review of the final policy recommendations, a summary of the contributions of this study, and a few suggestions for further research.

### 6.1 Synopsis

At issue in this study is the current policy of designating Special Use Airspace (SUA) for either air or space transportation at any given time. This is a strategic policy, in that air/space traffic conflicts are resolved well in advance. It prioritizes safety and is operationally simple, but it forces one mode of operations to disrupt the other. This involves costs, which can be expected to rise with continued growth in air traffic or especially if frequent-flying reusable launch vehicles (RLVs) are developed. The purpose of this study is to compare the current policy with potential tactical alternatives in light of uncertain future developments.

#### 6.1.1 Analytical Approach

An integrated engineering/policy analysis was developed to approach this problem. The key issues of safety, efficiency, equity, and service were considered, with efficiency information selected as most important to choosing between the policy options. An approximation of the total annual disruption cost,  $J$ , was constructed as a function of four factors (Eq. 1):

- $N$  – average air/space traffic conflicts per space transportation event
- $E$  – average space transportation events per year
- $D$  – average traffic disruption (airborne delays) per conflict
- $C$  – average cost per unit disruption (assumed constant: \$62.50 per minute)

$N$  was identified as the most critical of these factors for this analysis, being the most directly controlled by aspects of the policy decision, and the least situation-dependent. An analytical Airspace Conflict Model (ACM) was derived to calculate the average number of conflicts associated with restricting a region of airspace for a period of time (Eq. 10). The validity of the ACM was confirmed using actual air traffic data. However, the precision of ACM predictions was found to depend on the accuracy of the input air traffic density information.

From the ACM and analysis of  $E$ ,  $D$ , and  $C$ , six fundamental factors of  $J$  were identified for the technical analysis.

### **6.1.2 Technical Findings**

In the first part of the technical analysis, the sensitivity of  $J$  to the total and expected ranges of the six fundamental factors, both individually and collectively, was explored. The current value of  $J$  was estimated to be just under \$1 million. The entire conceivable range of  $J$  was found to span nine orders of magnitude, within which a range of roughly \$100 to \$8 million was fairly plausible. Of the six factors, the size of the restricted airspace had by far the largest effects on  $J$ , which was found to be insensitive only to the relative velocity of the air traffic. Finally,  $J$  was found to be 100 times as sensitive to controllable policy factors (SUA size and duration) as to market-driven factors (annual space transportation events and average air traffic density), varied *ceteris paribus* across their expected ranges.

The second part of the technical analysis investigated four scenarios of combined changes in the fundamental factors, resulting in two principal findings. First,  $J$  was found to be notably more sensitive to the size of the restricted airspace than to the restricted duration and traffic density combined, supporting the hypothesis that this factor dominates all others in affecting efficiency. Second, rapid growth in space transportation events, such as might accompany the development of a revolutionary RLV, was found to substantially increase  $J$  in the absence of preventive policy action, but various measures were found to mitigate this effectively. No interaction effects or unexpected behavior were observed in the scenario analyses.

### **6.1.3 Policy Analysis**

The technical analysis produced needed results, but was too narrow in scope to lead to practical policy recommendations. Consequently, a comprehensive but qualitative policy analysis was conducted, attempting to include:

- All key issues – safety, efficiency, equity, service
- All major stakeholders – 3 classes of operators, 4 organizations functioning as system managers, and Congress
- Other policy considerations – issue importance, consensus, barriers to implementation

For the comprehensive analysis, four policy options were assessed:

- reduce the size of the restricted airspace ( $S$ )
- reduce the duration for which the airspace is restricted ( $T$ )
- coordinate space transportation events with air traffic to reduce traffic density ( $\rho$ )
- shift launch operations to a remote location to eliminate disruption

## 6.2 Recommendations

The primary conclusion of this analysis is that the total annual cost of air traffic disruption due to space launch is currently insignificant (approximately \$1 million).

However, if this cost were to increase sufficiently to warrant action, and if a policy decision had to be made immediately, the best recommendation appears to be a combination of several options, some short-term and others that may be implemented over time.

First, the schedules of all upcoming but not imminent launches (say at least six weeks away, but not more than a year off) should be examined. Any that are planned for peak air traffic periods should be reconsidered, assessing the cost/difficulty that would be involved in rescheduling them for off-peak periods. If the launch windows prove relatively flexible, all events (in the same time frame) planned for the transition intervals should also be examined, to see if any can be rescheduled for the minimum air traffic periods.

Second, those operations that cannot be easily rescheduled for off-peak times should be considered for launch from a remote location. Depending on the supply of launch vehicles, payload matching, and orbital requirements, it may not be possible to schedule such operations for a year or so, but this is at least worth looking into.

Finally, the FAA and DOD should investigate the following four possibilities for moving toward more tactical aerospace traffic management to reduce disruption costs:

1. Reduce the duration for which SUA is restricted in general, especially activation well in advance of (more than 30 minutes before) launch.
2. Unless (1) is feasible and able to be implemented soon, allow controlled aircraft to transit the SUA until a shorter period before actual events, only maintaining the full restricted durations for uncontrolled air traffic.
3. Reduce the SUA requirements for the Pegasus and similarly "safe" vehicles, as long as any actual rocket stages are launched over water in remote areas.
4. Reduce the size of the SUA restricted for at least some launches, such as those involving particular trajectories.

Depending on how soon the various elements could be implemented, and to what extent, these recommendations could significantly reduce the disruption cost even in the short term (within two years), and should be able to keep it below any relevant maximum through the medium term (less than twenty years) even if air traffic continues to grow and efficient new RLVs are developed that result in substantial growth in space transportation events.



### 6.3 Contributions

This research has made contributions in at least four areas:

- SUA impact analysis – this study has identified the key issues and stakeholders to consider, constructed an appropriate analytical framework, and provided the kind of quantitative information about the magnitude of the problem and its sensitivity to changes in critical factors that the decision-makers sought.
- Airspace/traffic conflict analysis – the Airspace Conflict Model (ACM) developed for this research could facilitate rapid policy analysis not only in this area, but potentially for any situations involving airspace restriction (bad weather, equipment failure, etc.). While derived from a combination of existing theories it seems to be a new approach, and it certainly appears to be of value for air traffic analysis.
- Policy recommendations – although the principal finding turned out to be no need for change in the short term, this analysis has fulfilled its goal of identifying the best decision based on current information, as well as offering ways to improve this decision with new information or developments.
- Integrated engineering/policy analysis – while the methods herein make no claim to being the “best” way to analyze Complex, Large-scale, Integrated, Open Systems (CLIOS), hopefully this review of general procedures and their detailed application to this problem in some way helps to advance the state of this relatively nascent art.

### 6.4 Suggestions for Further Research

As is often the case with research – and especially with prospective studies – this analysis has uncovered additional topics that would be valuable for future research. A few possibilities include:

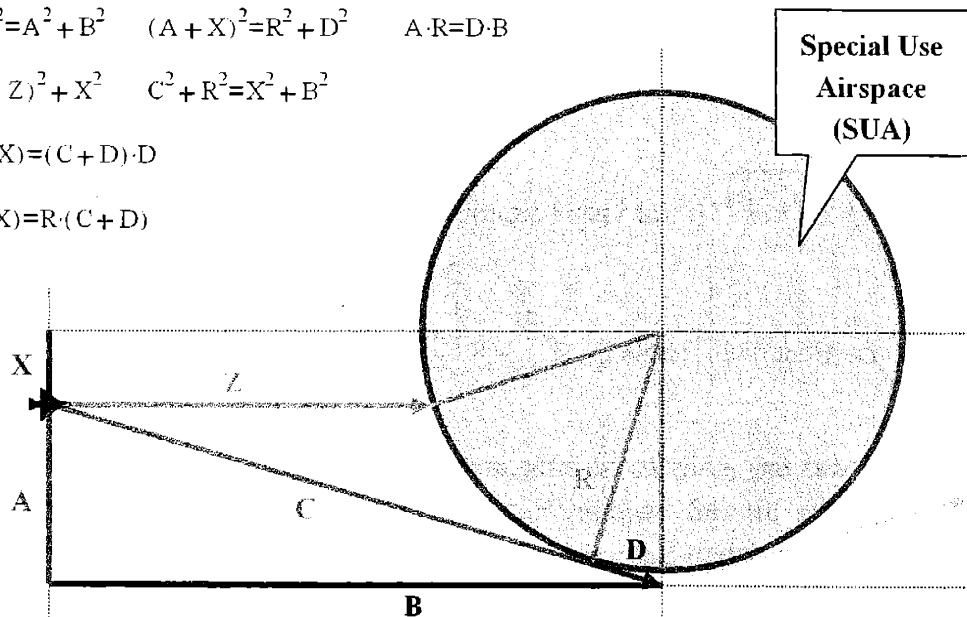
- Other geographic areas – mainly requires investigating the traffic densities.
- Specific vehicle/mission scenarios – could affect SUA definition and annual events.
- Modeling improvements – especially regarding safety, deviation, and costs.
- Political economy – appropriate distribution of costs and access.
- Technology assessment – the potential of new technologies to alter SUA.
- Launch scheduling – feasibility/cost of moving space launch windows.

## Appendix: Modeling Deviation

As explained in section 4.1.1, the disruption or path extension associated with a flight deviating around Special Use Airspace (SUA) depends on specifically when and how the flight is re-routed, which is actually up to the pilot or controller. For this analysis, it was decided to model a double tangent deviation. This procedure is initiated at the minimum Alert Zone distance ( $Z$ ) from the SUA boundary, at which point a new heading is adopted that will just clear the SUA at the point of closest approach. Modeling the SUA as a circular region, this new heading is tangent to the boundary. Midway across the side of the SUA, the second maneuver results in a complementary heading, tangent to the other side. This leads to rejoining the original route at the same distance,  $Z$ , beyond the SUA as it was originally left before it. There the final maneuver is to simply return to the original heading. Consisting of purely linear flight segments and three simple heading changes, this is probably the simplest deviation procedure for the pilot. At the same time, it is also a reasonable approximation of the minimum deviation required to circumvent the SUA for a given  $Z$ .

Seven geometric components of the double tangent deviation are labeled in Figure 6.1. These comprise several right triangles and similar triangles, which enable the use of geometric relationships to define the seven equations listed below.

$$\begin{aligned} (C+D)^2 &= A^2 + B^2 & (A+X)^2 &= R^2 + D^2 & A \cdot R &= D \cdot B \\ R^2 &= (B-Z)^2 + X^2 & C^2 + R^2 &= X^2 + B^2 \\ A \cdot (A+X) &= (C+D) \cdot D \\ B \cdot (A+X) &= R \cdot (C+D) \end{aligned}$$



*Figure 6.1 Geometric Components and Equations of the Double Tangent Deviation*

Simultaneous solution of these equations in Figure 6.1 can lead to descriptions of B, C, and D in terms of Z, R, and X:

$$B = Z + (R^2 - X^2)^{\left(\frac{1}{2}\right)}$$

$$C = \left[ \left[ 2 \cdot Z + 2 \cdot (R^2 - X^2)^{\left(\frac{1}{2}\right)} \right] \cdot Z - Z^2 \right]^{\left(\frac{1}{2}\right)}$$

$$D = -R \cdot \frac{\left[ R \cdot \left[ \left[ 2 \cdot Z + 2 \cdot (R^2 - X^2)^{\left(\frac{1}{2}\right)} \right] \cdot Z - Z^2 \right]^{\left(\frac{1}{2}\right)} - \left[ Z + (R^2 - X^2)^{\left(\frac{1}{2}\right)} \right] \cdot X \right]}{\left[ \left[ -2 \cdot Z - 2 \cdot (R^2 - X^2)^{\left(\frac{1}{2}\right)} \right] \cdot Z + Z^2 + X^2 \right]}$$

This in turn enables calculation of the original path length (2B) and the re-routed path length (2C+2D), the difference between which is the flight extension, or disruption:

$$\left[ \left[ 2 \cdot Z + 2 \cdot (R^2 - X^2)^{\left(\frac{1}{2}\right)} \right] \cdot Z - Z^2 \right]^{\frac{1}{2}} - R \cdot \frac{\left[ R \cdot \left[ \left[ 2 \cdot Z + 2 \cdot (R^2 - X^2)^{\left(\frac{1}{2}\right)} \right] \cdot Z - Z^2 \right]^{\left(\frac{1}{2}\right)} - \left[ Z + (R^2 - X^2)^{\left(\frac{1}{2}\right)} \right] \cdot X \right]}{\left[ \left[ -2 \cdot Z - 2 \cdot (R^2 - X^2)^{\left(\frac{1}{2}\right)} \right] \cdot Z + Z^2 + X^2 \right]} - \left[ Z + (R^2 - X^2)^{\left(\frac{1}{2}\right)} \right]$$

Or, setting  $(Z + \sqrt{R^2 - X^2}) \equiv N$  for visual simplification:

$$\text{Deviation} := 2 \cdot \left[ \left[ (2 \cdot N) \cdot Z - Z^2 \right]^{\frac{1}{2}} - R \cdot \frac{\left[ R \cdot \left[ (2 \cdot N) \cdot Z - Z^2 \right]^{\left(\frac{1}{2}\right)} - (N) \cdot X \right]}{\left[ (-2 \cdot N) \cdot Z + Z^2 + X^2 \right]} - (N) \right]$$

This equation was originally to be integrated with respect to X to analytically determine the average value for aircraft encountering the SUA at any position across its width, but regrettably, no formulation that could be integrated was found. Therefore the average value was determined empirically by averaging 10,000 calculations across the SUA width for each case (each combination of R and Z) analyzed in this thesis. This led to quantitative solutions, but the lack of an equation for average deviation precluded a final equation for the total annual disruption cost (J), which is why this equation and its partial derivatives with respect to each factor could not be presented in the sensitivity analyses of Chapter 4.

## Abbreviations

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Abbreviations abound in aerospace, policy, and theoretical discussion, so naturally a number appear in this thesis. For a convenient reference, all of these abbreviations are listed below in alphabetical order, grouped under acronyms or elements of equations.

### Acronyms

ACM	Airspace Conflict Model
ARTCC	Air Route Traffic Control Center
AST	Office of Assoc. Admin. for Commercial Space Transportation, FAA
AZ	Alert Zone
ATM	Air Traffic Management
CLIOS	Complex, Large-Scale, Integrated, Open Systems
CNS	Communications, Navigation, and Surveillance
CRCT	Collaborative Routing Coordination Tools
DOD	Department of Defense
EELV	Evolved Expendable Launch Vehicle
ELV	Expendable Launch Vehicle
ETMS	Enhanced Traffic Management System
FAA	Federal Aviation Administration
FACET	Future ATM Concepts Evaluation Tool
FCA	Flow Constrained Area (in CRCT)
GA	General Aviation
HT-HL	Horizontal takeoff, horizontal landing (flight profile)
IFR	Instrument Flight Rules
KSC	Kennedy Space Center
NAS	National Airspace System
NASA	National Aeronautics and Space Administration

PZ	Protected Zone
RLV	Reusable Launch Vehicle
ST	Space Transportation
SUA	Special Use Airspace
TAAM	Total Airport and Airspace Modeler
TRACON	Terminal Radar Approach Control
US	United States of America
VFR	Visual Flight Rules
VT-HL	Vertical takeoff, horizontal landing (flight profile)
VT-VL	Vertical takeoff, vertical landing (flight profile)

### Elements of Equations

$a$	Cross-sectional area of the SUA/PZ
$A$	Cross-sectional area of the air traffic flow
$C$	Cost per unit disruption
$D$	Disruption (e.g., delay minutes) per conflict
$E$	Space transportation events (launch/re-entry) per year
$J$	Total annual air/space traffic disruption cost
$N$	Number of air/space traffic conflicts per space event
$R$	Radius of SUA/PZ (if circular, else radius of equiv. circular area)
$S$	Volume (or area if 2-D) of airspace taken up by SUA/PZ
$T$	Duration for which SUA/PZ is restricted
$V$	Average velocity of air traffic relative to SUA/PZ
$Z$	Alert Zone range (distance/time at which conflicts are resolved)
$\phi$	Obstruction; fraction of air traffic encountering SUA/PZ
$\lambda$	Airspace arrival rate (aircraft entering/leaving per unit time)
$\rho$	Air traffic density (aircraft per unit volume/area of airspace)
$\tau$	Average time for air traffic to cross SUA/PZ

## References

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- <sup>1</sup> Mohleji, Satish C, Jonathan H Hoffman, and William K MacReynolds. "Impact Analysis of Commercial Space Launches: Potential User Cost to Civil Aviation." McLean, VA: MITRE Center for Advanced Aviation System Development, WN 97W0000061. September 1997.
- <sup>2</sup> *U.S. Airline Industry Facts, Figures, and Economic Analyses* [website]. Air Transport Association Office of Economics, March 2002 [cited 28 April 2002]. Available from <http://www.airlines.org/public/industry/display1.asp?nid=1026>.
- <sup>3</sup> *ACI Traffic Data: World airports ranking by total movements - 2000* [website]. Airports Council International, 2001 [cited 28 April 2002]. Available from <http://www.airports.org/traffic/movements.html>.
- <sup>4</sup> "Administrator's Fact Book." Washington, DC: Federal Aviation Administration. February 2002. Available from <http://www.atctraining.faa.gov/factbook>.
- <sup>5</sup> ATA Office of Economics. "State of the US Airline Industry: A Report on Recent Trends for US Carriers." Washington, DC: Air Transport Association of America, Inc. 6 March 2002. Available from <http://www.airlines.org/public/industry/bin/state.pdf>.
- <sup>6</sup> Ott, James. "Welcome to Gridlock, All Flights Delayed." *Aviation Week & Space Technology*, 25 October 1999.
- <sup>7</sup> *Current Market Outlook 2001* [website]. Boeing Corp., June 2001 [cited 9 March 2002]. Available from <http://www.boeing.com/commercial/cmo/>.
- <sup>8</sup> Bond, David. "Optimism on Surface, Skepticism Beneath." *Aviation Week & Space Technology*, 18 March 2002.
- <sup>9</sup> Donohue, George L, Andres G Zellweger, Herman Rediess, and Christian Pusch, eds. *Air Transportation Systems Engineering*. Edited by Paul Zarchan. Vol. 193, *Progress in Astronautics and Aeronautics*. Reston, VA: American Institute of Aeronautics and Astronautics, 2001.
- <sup>10</sup> Wilson, James Q. *Bureaucracy: What Government Agencies Do and Why They Do It*. USA: Basic Books, 1989.
- <sup>11</sup> Kingdon, John W. *Agendas, Alternatives, and Public Policies*. 2<sup>nd</sup> ed. New York, NY: HarperCollins College Publishers, 1995.
- <sup>12</sup> Nolan, Michael S. *Fundamentals of Air Traffic Control*. 3<sup>rd</sup> ed. Pacific Grove, CA: Brooks/Cole, 1999.
- <sup>13</sup> Wall, Robert, and David A Fulghum. "UAVs Spotlited As Defense Priority." *Aviation Week & Space Technology*, 11 February 2002.
- <sup>14</sup> Brown, Alan. *Two UAV Science Missions Selected* [website]. The Dryden X-Press, NASA Dryden Research Center, 31 May 2001 [cited 30 April 2002]. Available from [http://www.dfrc.nasa.gov/PAO/X-Press/stories/053101/res\\_uav.html](http://www.dfrc.nasa.gov/PAO/X-Press/stories/053101/res_uav.html).

- <sup>15</sup> *Space Statistics* [website]. NASA Office of Space Flight, 2002 [cited 30 April 2002]. Available from <http://www.hq.nasa.gov/osf/spacestat.html>.
- <sup>16</sup> Pietrobon, Steven. *Steven Pietrobon's Space Archive* [website]. 7 November 2001 [cited 30 April 2002]. Available from <http://www.sworld.com.au/steven/space/>.
- <sup>17</sup> Pace, Scott. "U.S. Access to Space: Launch Vehicle Choices for 1990-2010." Santa Monica, CA: RAND, Project Air Force, R-3820-AF. March 1990.
- <sup>18</sup> Isakowitz, Steven J, Joseph P Hopkins, Jr., and Joshua B Hopkins. *International Reference Guide to Space Launch Systems*. 3<sup>rd</sup> ed. Reston, VA: American Institute of Aeronautics and Astronautics, 1999.
- <sup>19</sup> Associate Administrator for Commercial Space Transportation, and Commercial Space Transportation Advisory Committee. "2001 Commercial Space Transportation Forecasts." Washington, DC: Federal Aviation Administration. May 2001. Available from [http://ast.faa.gov/comstac\\_info/reports/](http://ast.faa.gov/comstac_info/reports/).
- <sup>20</sup> Associate Administrator for Commercial Space Transportation. *About the Office of the Associate Administrator for Commercial Space Transportation* [website]. Federal Aviation Administration, 2002 [cited 30 April 2002]. Available from <http://ast.faa.gov/about/>.
- <sup>21</sup> Associate Administrator for Commercial Space Transportation. "Commercial Space Transportation: 2001 Year In Review." Washington, DC: Federal Aviation Administration. January 2001. Available from [http://ast.faa.gov/launch\\_info/yir/](http://ast.faa.gov/launch_info/yir/).
- <sup>22</sup> Hannigan, Russell J. *Spaceflight in the Era of Aero-Space Planes*. Malabar, FL: Krieger Publishing Co., 1994.
- <sup>23</sup> *Space Transportation: About SLI - 2<sup>nd</sup> Generation RLV* [website]. NASA Marshall Space Flight Center, 2002 [cited 30 April 2002]. Available from <http://std.msfc.nasa.gov/sli/aboutsli.html>.
- <sup>24</sup> *Advanced Space Transportation Program* [website]. NASA Marshall Space Flight Center, 2002 [cited 30 April 2002]. Available from <http://std.msfc.nasa.gov/ast/astp.html>.
- <sup>25</sup> Bond, David. "Commercial Aviation On the Ropes." *Aviation Week & Space Technology*, 18 September 2000.
- <sup>26</sup> Huddleston, Tim. "SLI: A Next Step for Mankind." *Space News*, 24 September 2001.
- <sup>27</sup> Sussman, Joseph M, and Rebecca Dodder. "The Concept of a "CLIOS Analysis" Illustrated by the Mexico City Case." Paper presented at the ESD International Symposium, Cambridge, MA, 30 April 2002.
- <sup>28</sup> Sussman, Joseph M. *Introduction to Transportation Systems*. Boston: Artech House, 2000.
- <sup>29</sup> de Neufville, Richard. *Applied Systems Analysis : Engineering Planning and Technology Management*. USA: McGraw-Hill, Inc., 1990.
- <sup>30</sup> Bardach, Eugene. *A Practical Guide for Policy Analysis: The Eightfold Path to More Effective Problem Solving*. New York, NY: Seven Bridges Press, LLC, 2000.

- <sup>31</sup> Weimer, David L, and Aidan R Vining. *Policy Analysis: Concepts and Practice*. 3<sup>rd</sup> ed. Upper Saddle River, NJ: Prentice-Hall, 1999.
- <sup>32</sup> Stokey, Edith, and Richard Zeckhauser. *A Primer for Policy Analysis*. New York, NY: W. W. Norton & Co., 1978.
- <sup>33</sup> Fiorino, Frances. "Passengers Enraged, But Does Industry Care?" *Aviation Week & Space Technology*, 14 June 1999.
- <sup>34</sup> Silbergeld, Mark. *Consumer's Union Calls on Congress to Address Promptly Reid Bills on Airline Passenger Rights, Competition* [website]. Consumer's Union, 29 January 2001 [cited 7 April 2002]. Available from <http://www.consumersunion.org/other/reiddc101.htm>.
- <sup>35</sup> Falker, John M, III. "Conflict Analysis of Air and Space Modes of Transportation." Master of Science, Massachusetts Institute of Technology, 1999.
- <sup>36</sup> Bond, David. "As Delay Season Nears, FAA, Airlines See Hope." *Aviation Week & Space Technology*, 14 May 2001, p. 91.
- <sup>37</sup> Odoni, Amedeo R, Jeremy Bowman, Daniel Delahaye, John J Deyst, Eric Feron, R John Hansman, Khashif Khan, James K Kuchar, Nicolas Pujet, and Robert W Simpson. "Existing and Required Modeling Capabilities for Evaluating ATM Systems and Concepts: Summary Report." Cambridge, MA: MIT International Center for Air Transportation, ICAT-98-2. March 1997.
- <sup>38</sup> Carlson, L S, and L R Rhodes. "Operational Concept for Traffic Management Collaborative Reroute Coordination Tools." McLean, VA: MITRE Center for Advanced Aviation System Development, MP92W0000106. April 1998.
- <sup>39</sup> Bilimoria, Karl D, Banavar Sridhar, Gano Chatterji, Kapil Sheth, and Shon Grabbe. "FACET: Future ATM Concepts Evaluation Tool." Paper presented at the 3<sup>rd</sup> USA/Europe Air Traffic Management R&D Seminar, Naples, Italy, June 2000.
- <sup>40</sup> *Collaborative Routing Coordination Tools* [website]. MITRE Center for Advanced Aviation System Development, October 2001 [cited 9 March 2002]. Available from <http://www.caasd.org/proj/crct/>.
- <sup>41</sup> Krozel, Jimmy, Mark Peters, Karl D Bilimoria, Changkil Lee, and Joseph S B Mitchell. "System Performance Characteristics of Centralized and Decentralized Air Traffic Separation Strategies." Paper presented at the 4<sup>th</sup> USA/Europe Air Traffic Management R&D Seminar, Santa Fe, NM, USA, December 2001.
- <sup>42</sup> Dumoulin, Jim. *NASA Space Shuttle Launches* [website]. Kennedy Space Center, 31 May 2000 [cited 9 March 2002]. Available from <http://science.ksc.nasa.gov/shuttle/missions/missions.html>.
- <sup>43</sup> Pufpaff, Duane M. *The Closing Circle: Nature, Man, and Technology by Barry Commoner -- An Article Review* [website]. 10 June 1997 [cited 7 April 2002]. Available from <http://www.tamucc.edu/~whatley/padm5370/read04a.htm>.
- <sup>44</sup> Stone, Deborah A. *Policy Paradox: The Art of Political Decision Making*. Revised ed. New York, NY: W. W. Norton & Co., 2002.



- <sup>45</sup> Gerston, Larry N. *Public Policy Making: Process and Principles*. New York, NY: M. E. Sharpe, 1997.
- <sup>46</sup> "Sea Launch User's Guide, Revision B." Seattle, WA: Boeing Commercial Space Co. June 2000. Available from [http://www.sea-launch.com/special/sea-launch/user\\_guide/user\\_guide.pdf](http://www.sea-launch.com/special/sea-launch/user_guide/user_guide.pdf).
- <sup>47</sup> "2002 U.S. Commercial Space Transportation Developments and Concepts: Vehicles, Technologies, and Spaceports." Washington, DC: Associate Administrator for Commercial Space Transportation, Federal Aviation Administration. January 2002. Available from <http://ast.faa.gov/pdf/newtech.pdf>.
- <sup>48</sup> *National Think Tank Unveils Comprehensive Air Traffic Reform Blueprint* [website]. Reason Public Policy Institute, 22 February 2001 [cited 14 April 2002]. Available from <http://www.rppi.org/022201.html>.
- <sup>49</sup> *Eastern and Western Range (EWR) 127-1 Range Safety Requirements* [website]. Space and Missile Systems Center, US Air Force, 31 March 1995 [cited 14 April 2002]. Available from <http://ax.losangeles.af.mil/axz/ewr127-1/ewr127-1.htm>.
- <sup>50</sup> Committee of Space Launch Range Safety. "Streamlining Space Launch Range Safety." Washington, DC: National Research Council, 2000.
- <sup>51</sup> Brenlove, Milovan S. *Vectors to Spare: The Life of an Air Traffic Controller*. Ames, IA: Iowa State University Press, 1993.
- <sup>52</sup> Wells, Joel, Kathleen Bergen, and Ken Warren. "Airspace, Bridges, and Waterway Restrictions in Effect for All Space Shuttle Launches." Kennedy Space Center, FL: National Aeronautics and Space Administration, KSC Release No. 45-1. 13 April 2001.
- <sup>53</sup> Marsh, Alton K. "Skyway Patrol: How to Avoid Getting Chased by the FAA During a Shuttle Launch." *AOPA Pilot*, November 2000.