National Airspace Sector Occupancy and Conflict Analysis Models for Evaluating Scenarios under the Free-Flight Paradigm

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Free-Flight is a paradigm of aircraft operations that permits the selection of more cost-effective routes for flights rather than simple traversals between designated way-points, from various origins to different destinations. In this paper, we consider the effect of this paradigm on sector workloads and potential conflicts or collision risks, based on current and projected levels of commercial air traffic. To accomplish this task, we first develop an Airspace Sector Occupancy Model (AOM) that identifies the occupancies of flights within three-dimensional (possibly nonconvex) regions of space called sectors, by utilizing an iterative procedure to trace each flight’s progress through sector modules, that constitute the sectors. Next, we develop an Aircraft Encounter Model (AEM), which uses the information obtained from AOM to efficiently estimate the number and nature of blind-conflicts (i.e., conflicts under no avoidance or resolution maneuvers) resulting from a selected mix of flight plans. Besides identifying the existence of a conflict, AEM also provides useful information on the severity of the conflict and its geometry, such as the faces across which an intruder enters and exits the protective shell or envelope of another aircraft, the duration of intrusion, its relative heading, and the point of closest approach. For purposes of evaluation and assessment, we also develop a metric that provides a summary of the conflicts in terms of severities and difficulty of resolution. Finally, we apply these models to real data provided by the Federal Aviation Administration (FAA) for evaluating several Free-Flight scenarios under wind-optimized conditions. This study constitutes the first phase of a project undertaken by a joint FAA/Eurocontrol Collision Risk Modeling Group to develop tools for investigating air traffic control strategies and related workload and collision risk consequences under various scenarios. Follow-on work will incorporate pilot blunders, random deviations, and air traffic control man-in-the-loop maneuvers within the context of the Free-Flight paradigm, using the basic tools developed in the present study.
need for better tools and techniques to quantify and assess such risks.

The main motivation behind the Free-Flight paradigm is to provide the airlines with a greater flexibility in filing their flight plans using optimized point-to-point routes, without reliance on ground navigational aids, thereby resulting in more efficient and cost-effective flight trajectories. In the current system, navigation is dependent upon ground navigational aids, and communications are based on a hybrid of Very High Frequency line-of-sight and satellite-based techniques. In Free-Flight, pilots would receive real-time information regarding nearby flights, and on-board traffic advisories would provide cues for enforcing mandatory air traffic control separations. In a critical situation, an air traffic controller may interfere to resolve the conflict. Ostensibly, the FAA would retain some degree of oversight in approving these flight plans to ensure that they do not impose excessive workloads on any of the enroute air traffic control centers.

This paper summarizes a study conducted for the FAA Office of Operations Research and Investment Analysis to examine various airspace scenarios and to estimate blind conflicts (i.e., devoid of any conflict resolution maneuvers) and their geometries in enroute airspace for these situations. The specific contributions in this paper are the development of models to assess sector occupancies of aircraft and consequent workload characteristics under various prevalent scenarios, and to identify the types and geometry of future conflicts arising from new concepts of operations such as Free-Flight.

There exist several airspace analysis models and tools that provide some capability to quantify traffic density, conflict potential, and collision risk. We discuss these models below, and also briefly mention attempts that have been made to describe workload as a function of sector traffic density for the sake of completeness, because workload might be one of many variables involved in the assessment of collision risk in the future. A more extensive literature review on collision-risk tools and models is included in the Concept Paper prepared by the Joint FAA/Eurocontrol Separation and Collision Risk Modeling Group (Federal Aviation Administration/Eurocontrol, 1998).

The challenge in modeling collision risk for NAS operations is the nature of conflict paths, sector density, and intervention rules used by air traffic controllers (ATC) to separate traffic. Several past studies have attempted to develop collision risk metrics for various traffic scenarios. RATCLIFFE and FORD (1982) presented analytical and computer models that quantified the conflicts arising among different types of aircraft interacting in regions of uncontrolled airspace, and detailed some of the scenarios that could, in principle, pose higher threats than others. For example, it was found that collision threats were more likely to occur with 45° off from head-on than in dead-ahead scenarios over the range of speeds investigated. In a related study, FORD (1982) investigated the intrinsic safety features of various height rules in uncontrolled airspace operations using random distributions of flights in the vertical domain. The findings of this paper indicated that the collision risk under current height rules is greater than in a vertical random flight mode (a version of Free-Flight), unless significant height-keeping errors exist in the latter scenario.

Uncontrolled airspace flight analysis and collision risk assessment provide a first-order approximation viewpoint of potential conflicts under various airspace operational rules. Almost all conflict risk assessment models are intrinsically based on estimating the expected number of conflicts in the airspace over time. Many of the well-known models reported in the literature for deriving collision risk metrics over the North Atlantic have used procedural uncontrolled airspace assumptions (REICH, 1966; BROOKER, 1982). These models have been refined over the years in response to reduced separation standards (MACHOL, 1995).

The set of flight plans used in various collision risk studies have ranged from hypothetical random flights to actual flight schedules. GOODWIN and FORD (1984) described two methods to generate random aircraft traffic in a volume of airspace, and presented some interesting conflict statistics resulting from the scenarios modeled. In contrast, the approach taken in the present research effort uses actual FAA flight-plan data derived from the NAS database under various operational concepts.

MAGILL (1998) studied a comparison of blind-conflicts (referred to as “separation problems”) for a system that uses standard airways versus a Free-Flight system based on using approximate shortest paths over the airspace network (referred to as “direct routing”). A section of the European airspace bounded by the meridians at 10°W and 30°E, and the parallels at 36°N and 60°N was used for this purpose, using randomly generated flights that conform with a traffic demand forecast for the year 2005. The discrete event simulation package FLAME (Flexible Airspace Modelling Environment) was used to detect the number of encounters at various horizontal minimal separation requirements at different altitude levels, assuming a certain distribution of aircraft cruising at these speci-
fied altitudes. The results indicated that, for the current horizontal separation standard of 5 nautical miles, a 17% gain in traffic density capacity would be realized by using direct routing due to the decreased frequency of blind conflicts, assuming that the frequency of conflicts is proportional to the square of the traffic density.

Tomlin, Pappas, and Sastri (1998) presented a method to coordinate safe conflict resolution maneuvers between two aircraft in a free-flight scenario. Given a finite set of routine maneuvers (modeled as sequences of finite heading, altitude, or velocity changes), their methodology generates a safe conflict resolution, even in worst-case scenarios under uncertainty. Pilots may then select the most cost-effective course of action among these maneuvers, which safely avoids conflicts.

Quantifying collision risk requires some knowledge of the navigational performance of the aircraft and the reliability of onboard avionic systems. Several past studies have examined navigational performance capabilities of aircraft operating in jet routes (Polhemus and Livingston, 1981; HSU, 1982; Harrison and Moek, 1988; Ten-Have, Harrison, and Cox 1988). Other studies have concentrated on the development of suitable mathematical functions and models to estimate probabilities of lateral and vertical overlaps (Nagaoka, 1984; Hsu, 1982). In addition, Ford (1982) examined the protection offered by anti-collision aircraft devices such as the Traffic Alert and Collision Avoidance System. Although these studies do not attempt to estimate collision risk directly, they provide information on related elements that could be combined with blind-conflict models to produce more refined models that consider such aircraft maneuvers in resolving potential conflicts.

In examining the complex dynamics of air traffic control tasks, several studies have considered the temporal and spatial variations of flights to determine metrics that serve to assess workload measures. Some of these studies used extended time line analysis (Laudeeman and Palmer, 1995), and dynamic density concepts (Smith et al., 1998). Other studies have attempted to measure controller workload in Free-Flight environments (Hilburn et al., 1997; Wyndemere, Inc., 1996). In addition, several complex models have been developed to assess human response times in ATC/pilot interactions. One such example is the system MIDAS, that has been developed at the NASA Ames Research Center (Corker, Pisanch, and Bunzo, 1997).

All these efforts attempt to understand the dynamics of ATC/pilot control interactions under a specific set of circumstances. Few studies, however, provide insights into how the Free-Flight concept of operations will affect the distribution of workload among the various sectors covering the national airspace, or how it would affect the level of exposure of aircraft to collisions. The conceptual models developed in this paper provide the tools that could be used in conducting such a detailed study, and that could serve as foundational elements for a system that simulates ATC/pilot end-game dynamics.

The remainder of this paper is organized as follows. In Section 1, we develop the Airspace Sector Occupancy Model (AOM) to determine the occupancies of flights within three-dimensional regions of space called sectors. In Section 2, we develop the Aircraft Encounter Model (AEM), which uses the input from AOM to determine the existence and nature of conflicts among a set of flight plans. AEM provides information for detected conflicts such as the severity of the conflict, its geometry, the duration of intrusion, its relative heading, and the point of closest approach. Section 3 presents the application of these models to several air traffic scenarios provided by the FAA for the evaluation of several Free-Flight scenarios under wind-optimized conditions. Finally, Section 4 concludes the paper along with some possible future extensions of the proposed models.

1. AIRSPACE SECTOR OCCUPANCY MODEL

This section describes the AOM that can be used to determine the occupancies by aircraft of the modules and sectors that comprise the national airspace. The model examines a given set of flight-plans and mathematically describes their flight trajectories over a defined region of airspace to determine sector crossings and occupancies over time. This model can be used to assess sector workloads, and also serves to develop information that feeds into the AEM described next in Section 2.

1.1 Description of Input Data

The AOM requires as input the sector geometries and a set of aircraft flight plans, represented as a sequence of straight lines between way-points (dummy way-points could be specified to further discretize curvilinear flight trajectories). The model then processes this information to determine the occupancy of each sector by different flights over time. AOM also provides information on the sectors crossed by each individual flight path from a designated origin to a destination airport, and estimates time traversals over each sector encountered along this path.

The flight-plan information used in this study is
obtained from the FAA-Enhanced Traffic Management System database. Whenever a flight is assumed not to rely on ground-based navigational aids, a wind-optimized trajectory is adopted. Wind-optimized routing is that trajectory that will have the least possible impedance from the prevailing winds. Alternatively, the flight-plans that are input into AOM could consist of actual flight tracks extracted from system analysis recording data, or they could be projected flight plans that are predicted by various National Airspace Resource Investment Model (NARIM) flight-plan generators such as OPGEN, or by some independent flight generator. All the foregoing data sources contain way-points in latitude (degree), longitude (degree), and altitude (hundreds of feet), and time-tags corresponding to the crossing of each way-point. In some cases, the data optionally contains the originating and terminating airports.

The entire airspace over the United States is divided into twenty-one centers, each regulated by an air route traffic control center (ARTCC). Each of these centers is sub-divided into sectors. Sectors are well-defined airspace regions specified by the FAA for regulating air traffic, and are classified into three groups: low, high, and super-high sectors depending upon their floor and ceiling boundaries. Low sectors lie below the FL 240 (i.e., flight level 24,000 ft). High sectors extend between FL 240 and FL 350. The super-high sectors lie above FL 350. Each sector is composed of fixed point airspace units (FPA) and each of these FPAs is composed of modules. A module is an airspace region having a generally nonconvex polygonal crossection, and is defined by its vertices and its floor and ceiling altitudes (see Figure 1). Included in the set of vertices are pseudo-vertices, where a pseudo-vertex for a sector module is a vertex for some other module that is present on a vertical face of the given module, but is not an original defining vertex of its floor and ceiling. The points formed by the two-dimensional (2D) projection of either vertical edges or pseudo-vertices of a module onto its floor or ceiling are called nodes, and are used to define the floor and ceiling geometry of a sector module. Modules are stacked one over another to form an FPA, and several such adjacent FPAs form a sector. For analytical purposes, one may simply work with the modules that comprise a given sector, and ignore the FPA descriptions. The main source of enroute and terminal radar approach control sector information used in this study came from the FAA adaptation controlled environment system database. In addition, for the sake of convenience in implementation, certain dummy sectors are defined that envelope the region of concern so that flights that originate outside this region lie within this extended airspace.

1.2 Overview of the Overall Procedure

AOM first identifies the initial module within the defined airspace that is encountered by each flight. Once this initial module is detected, the exiting point and time of exit are identified. This point is found by checking whether the flight pierces any of the faces or the floor or the ceiling defining the module. The program also identifies the manner in which the flight exits the module, i.e., if the flight exits across a face, the floor, the ceiling, at a vertex, or across an edge. The next module the flight enters is then determined using the module information. This process of identifying each traversed module and the corresponding occupancy time is continued until the flight reaches its destination. The information regarding the sectors the flight passes through is then compiled by examining the modules that comprise each sector.

Note that, in this process of detecting sector occupancies, the curvature of the earth is ignored. The floors and ceilings of the sector modules are defined with respect to specified constant altitudes and are assumed to be parallel surfaces. The vertical faces of the sector modules are orthogonal to these surfaces (the cross-sections are invariant), and aircraft that are flying at constant altitudes are assumed to be following trajectories that are parallel to these surfaces. In essence, we can view each sector module via its 2D projected nonconvex polygonal structure, having vertices defined by longitude and latitude coordinates, and with this polygonal cross-section extending between the floor and the ceiling of the module. Furthermore, the piecewise linear trajectory followed by each aircraft, where the break-
points are defined by their longitudes, latitudes, and altitudes, can be examined using its 2D projected path, with a simultaneous check being made to ascertain floor and ceiling crossings in case the altitude is changing, to trace its occupancy within the various sector modules. Hence, in effect, the surface of the earth is flattened in space along the path of the aircraft, and, because of the manner in which the sectors and the flight trajectories are defined, this approach for determining sector occupancies conforms suitably with the specified data.

The procedures implemented within AOM can be summarized by four steps: data input, pre-processing, main routine, and post-processing. Data input involves reading the flight-plan (or track) data and airspace sector information from an external source as described above. Pre-processing refers to the creation of airspace mathematical boundaries, and the matching of vertices of adjacent modules. The main routine identifies the modules traversed by each flight and the related occupancy times. Finally, the post-processing step composes the various flight traversals over modules to provide aggregate information on sector occupancies and workloads.

1.3 Pre-processing and Adjacency

During pre-processing, adjacency information is gathered with respect to nodes, sector modules, and vertical faces. Consider a node \( v_m \), which might correspond to a real or a pseudo-vertex. All the sector modules that have \( v_m \) on the boundary of their 2D projections are considered to be adjacent with respect to \( v_m \) and are stored in a record for node \( v_m \). Sector modules adjacent to other sector modules are also identified and stored during pre-processing. For a sector module \( s \), let \( V_s \) be the set of nodes defining its floor and ceiling. Then, all the sector modules that share any node in \( V_s \) will be adjacent to \( s \) if they extend in part or whole over an altitude between the floor and ceiling of sector module \( s \).

Furthermore, for the purpose of tracing the trajectory of a flight through the nonconvex sector modules, consider the 2D projection or cross-section of a module as defined above (see Fig. 2). An inward gradient \( F_{ps} \) for a face \( p \) of a projected sector module \( s \) is that gradient vector orthogonal to the face such that a trajectory that starts at an interior point of this face \( p \) and moves in a direction \( d \), will reside in module \( s \) for some positive distance if and only if \( F_{ps} \cdot d \geq 0 \). The sector data derived from the FAA sector analysis and design tool reveals that the coordinates of the vertices for all the modules are recorded in a clockwise sequence. Hence, for any pair of vertices \( v_1 \) and \( v_2 \) defining the face \( p \), if the direction along the face is \( d_p = v_2 - v_1 = [d_{p1}, d_{p2}] \), then the inward gradient \( F_{ps} \) is given by \( F_{ps} = [d_{p2}, -d_{p1}] \).

Each vertex of a (projected) module is classified as Type (i) or Type (ii), based on its associated faces \( p \) and \( q \), as depicted in Figure 2. For a Type (i) vertex, the local neighborhood of the vertex is described by the conjunction of the faces \( p \) and \( q \). Hence, if a trajectory starts at this vertex and moves in a direction \( d \), then it would reside in module \( s \) for some positive step if and only if \( F_{ps} \cdot d \geq 0 \) and \( F_{qs} \cdot d \geq 0 \). For a Type (ii) vertex, the local neighborhood of the vertex is described by the disjunction of the faces \( p \) and \( q \). Hence, if a trajectory starts at this vertex and moves in a direction \( d \), then it would reside in module \( s \) for some positive step if and only if \( F_{ps} \cdot d \geq 0 \) or \( F_{qs} \cdot d \geq 0 \).

Finally, the occupancy model stores sector modules that are adjacent to each other with respect to a given projected vertical face. The projected vertical faces are distinguished from each other based on their defining end nodes. For any projected vertical face \( p \) having end nodes \( v_1 \) and \( v_2 \) (including pseudo-vertex-induced nodes), all (adjacent) sector modules containing nodes \( v_1 \) and \( v_2 \) are considered adjacent with respect to \( p \). These sector modules can be determined from the adjacency information with respect to the nodes. The model also classifies the sector modules that are adjacent with respect to a particular vertical face into two categories based on whether the sector module lies on the side toward the origin (equator on Greenwich meridian) or on
the side opposite to the origin. This additional information is used to identify the extreme vertical faces. These extreme faces define the external boundaries of either the defined airspace, or of vacuums (described in the sequel) that may be present in the airspace.

The pre-processing routine assigns each airport to a sector by checking the low-lying sector modules. Airports that lie outside the defined airspace would be associated with some dummy sector. Flight-plans are then pre-processed by identifying the sector module in which the flight trajectory originates, along with the initial point within the sector module, and the starting time. The procedure then enters the main processing routine.

1.4 Main Routine for Determining Sector Module Occupancies

Consider a flight path that is comprised of linear discretized flight segments having break points represented in terms of the coordinates \( wp_1, wp_2, \ldots, wp_n \), that it traverses. Let any linear segment \( i \) of the trajectory be defined as \( wp_i + \lambda d \) for \( 0 \leq \lambda \leq 1 \), where \( d = wp_{i+1} - wp_i \), for \( i = 1, \ldots, n-1 \). Figure 3 illustrates this situation for a cross-sectional view of the modules depicted in Figure 1. Iteratively, suppose that for the \( i \)th segment and corresponding way-point \( wp_i \), we know the sector module \( s \) in which this current way-point lies, and its actual location in this sector module (interior point, (relative) interior of a face, or at a vertex). This is initially determined during the pre-processing routine, and is sequentially deduced as follows (for details, see SHERALI et al., 1998).

Examining the vertical faces \( p \) of module \( s \) for which \( F_{ps} \cdot d < 0 \), as well as the floor and ceiling of \( s \) in case the altitude is decreasing or increasing, respectively, we begin by finding a first face that the straight-line trajectory \( wp_i + \lambda d \) intersects (internally or at a boundary point). Suppose that this occurs at \( \lambda = \lambda_i \). If \( \lambda_i > 1 \), then we revert to the point corresponding to \( \lambda = 1 \), and consider the next linear segment. Else, this point lies on the boundary of the sector module, being located on the interior of a vertical face, at the interior of a horizontal face, or on a vertical edge, on a horizontal edge, or at a vertex. Based on the particular case, and using the adjacency information, the possible sector modules into which the flight may have entered are selected. (Note that the occupancy of module \( s \) can continue in case we have just internally glanced a Type (ii) vertex, as depicted at point \( A \) in Figure 3.) This is automatically determined in the next loop of the procedure, which ascertains the sector that will be occupied as the trajectory continues (using the next linear segment in case \( \lambda = 1 \)). The dot products of the various inward gradients of the intersected faces with \( d \) are used to ascertain this as described before. Note that, if more than one sector module is entered, as when a flight moves along a vertical face or along a horizontal edge, only one of such modules will be considered, with a preference given to the currently occupied module. Hence, for the segment from \( wp_i \) to \( wp_{i+1} \) in the example of Figure 3, assuming a constant altitude trajectory, the procedure would first encounter the node \( A \) and detect that the trajectory will continue to occupy sector module \( s \).
Next, it would find the intersection point \( B \) and determine that the flight will now enter sector module \( s + 1 \). Within this new sector module, the particular linear trajectory will end before intersecting any boundary faces, and the process would continue with the next linear segment.

In closing this section, we mention that, due to inaccuracies in existing FAA sector data, there occur certain undefined airspace regions between adjacent sectors that we call vacuums. For the most part, by enforcing nodes that have slightly perturbed locations to define the same point, we can circumvent the creation of such vacuums. Still, vacuums too large to be resolved by this modification of data may exist, and we adopt the following strategy to accommodate this situation. During pre-processing, we identify all the vacuums that are present in the airspace and store the information regarding their defining vertical faces. Then, in the above procedure, if the routine is not able to identify the sector module that the flight enters based on the adjacency information, it assumes that the flight has entered a vacuum. The flight's segments are then checked to see when and if they cross any of the vacuum's extreme faces. Based on the first extreme face encountered, the procedure identifies the sector module entered and continues as usual, possibly terminating in the identified vacuum space itself.

2. AIRCRAFT ENCOUNTER MODEL

The AEM described in this section estimates blind conflicts in the airspace under various concepts of
operations. AEM uses the outputs of AOM to determine all possible conflicts among aircraft pairs occurring in a prescribed volume of airspace. The main goal of AEM is to assess the precise geometry of conflicts between pairs of aircraft. AEM is expected to be used in airspace analyses as a screening tool to understand aircraft conflict patterns under various new concepts of operations. The FAA/Eurocontrol Collision Risk Modeling Group identified conflict geometry and scenario evaluation as one of the basic tasks in the process of developing a toolbox of collision risk models. AEM is a first step in this direction.

The first major task in AEM is the extraction of flight proximity information. This is done through the creation of three data structures containing temporal, spatial, and sector adjacency information. The next step considers these proximal flights in time and space and initiates the flight conflict analysis. After individual aircraft pairs are studied in detail using analytic trajectory equations, suitable conflict analysis statistics are computed and aggregated.

2.1 Box Model for Blind Conflict Risk Analysis

Consider any pair of aircraft $A$ and $B$ and suppose that their trajectories are known, and that we have identified segments of durations (not necessarily of equal length) over which the trajectories of these aircraft are (approximately) linear. Assume that each aircraft is moving at a constant velocity over this duration (the velocities might change from one duration segment to the next). For convenience in computations, the aircraft locational information that is provided in terms of the (latitude, longitude) = $(\alpha, \beta)^o$ data, and the altitude $h$, where $90^o \leq \alpha \leq 90^o$, and $0^o \leq \beta \leq 360^o$ is converted from spherical coordinates to a Cartesian system as shown in Figure 4. Here, the origin $O$ is taken to be the center of the earth, with the $x_1$-axis oriented from $O$ toward $(0, 0)^o$, the $x_2$-axis oriented from $O$ toward $(0, 90)^o$ (orthogonal to the $x_1$-axis in the horizontal plane), and with the $x_3$-axis oriented from $O$ toward $(90, 0)^o$. Hence, given $(\alpha, \beta)^o$ and $h$, the Cartesian coordinates in $x = (x_1, x_2, x_3)$-space is given as

$$x = (x_1, x_2, x_3) = (R + h)(\cos \alpha \cos \beta, \cos \alpha \sin \beta, \sin \alpha),$$

where $R$ is the radius of the earth. Accordingly, for any time segment of duration $T$ hours over which the trajectories of $A$ and $B$ are linear, let

$$x^A = \bar{x}^A + \lambda d^A$$

for $0 \leq \lambda \leq 1$ \hspace{1cm} (2a)

denote the trajectories of aircraft $A$ and $B$, respectively, where $x^A \in R^3$ denotes the coordinates of aircraft $A$, $\bar{x}^A$ is its initial position, and $\bar{x}^A + d^A$ is its final position over the given segment of duration $T$, and where the quantities for aircraft $B$ are defined similarly.

In this section, we consider a generalization of the box model of Reich (1966) that examines rectangular proximity shells as illustrated in Figure 5. Here, $S_1$, $S_2$, and $S_3$, respectively, denote the standard in-trail (along track), lateral (across track), and vertical separation parameters, that must be maintained (5 nautical miles in the in-trail and lateral directions, along with a vertical separation of 1000 feet). Any intrusion of another aircraft (treated as a point) within this shell poses a conflict risk. Note that, alternatively, we could consider cylindrical proximity shells having a circular or elliptical cross-section in the plane of the aircraft. The analysis would be similar to that described in the sequel, with the linear system (6) in $\lambda$ below being replaced by an appropriate quadratic equation. Our choice here is for the sake of convenience in computations, and also serves an illustrative purpose.

In addition, to identify different levels of conflict severity, we will also consider two other alternative tighter proximity shells in the sequel, having designated dimensions of $S_1'$, $S_2'$, and $S_3'$ as illustrated in
Figure 5. The dimension of these proximity shells might depend on the particular (type of) aircraft A. Note that the aircraft need not be centered in the box to perform the following type of analysis, although for simplicity in exposition, we assume this to be the case. We remark here that, besides identifying the proximity shell pierced, the intensity of any conflict can be further classified according to the actual (minimal) separation distance while the intruder is within such a proximity shell, the duration of this intrusion, its entry and exit faces, and its relative heading with respect to the primary aircraft A. This defines the geometry of the conflict, and influences the threat of collision and the degree of difficulty in resolving the conflict. Note that these entities are to be defined as the box that defines the proximity shell under consideration moves with the aircraft in the same direction of motion.

Now, over the duration of time for which the trajectories of these aircraft are described by Eqs. 2a and 2b, consider A as the focal aircraft and B as the intruder. (The roles of being a focal aircraft and an intruder can be reversed symmetrically while considering this same duration for the aircraft pair.) Let us first transform the coordinate system from the three-dimensional x-space to a convenient y-space representation using the affine transformation,

$$x = \bar{x}^A + Qy,$$

where $Q$ is a nonsingular $3 \times 3$ matrix having orthonormal columns, and where the $y_1$-axis corresponds to the in-trail direction of motion ($d^A$) of aircraft $A$, the $y_2$-axis is orthogonal to the $y_1$-axis and lies in the plane spanned by $d^A$ and the position vector $\bar{x}^A$ emanating from the center of the earth, with the positive direction making an acute angle with $\bar{x}^A$, and the $y_3$-axis is orthogonal to the $(y_1, y_3)$ plane. This latter axis represents the wing span, and we arbitrarily take the positive $y_2$-axis to point to the left of the aircraft (see Figure 5).

Accordingly, we obtain

$$Q = \begin{bmatrix} Q_1 & Q_2 & Q_3 \\ \|Q_1\| & \|Q_2\| & \|Q_3\| \end{bmatrix},$$

where,

$$Q_1 = d^A, \quad Q_2 = Q_3 \times Q_1,$$

and

$$Q_3 = \bar{x}^A - d^A \left( \frac{d^A \cdot \bar{x}^A}{\|d^A\|^2} \right).$$

Note that $Q_1 = d^A$ defines the in-trail direction, and $Q_3$ lies in the plane spanned by the vector $\bar{x}^A$ from the center of the earth to the location of the aircraft $A$, and $d^A$, being orthogonal to $d^A$ and making an acute angle with $\bar{x}^A$. Hence, $Q_3$ is given by the difference between the vectors $\bar{x}^A$ and the projection of $\bar{x}^A$ onto the normalized direction $d^A$. Note that we assume $d^A \neq 0$, and that $\bar{x}^A$ and $d^A$ are noncollinear (or else the aircraft would be moving vertically with respect to the earth's surface). Furthermore, $Q_2$ is given by the cross-product of $Q_3$ and $Q_1$ following the right-hand cross product rule to ensure that the $y_2$-axis points to the left of the aircraft. Hence, denoting the $j$th component of the vector $Q_i$, for $i, j = 1, 2, 3$, we have,

$$Q_2 = \begin{bmatrix} Q_3(2)Q_1(3) - Q_3(3)Q_1(2) \\ Q_3(3)Q_1(1) - Q_3(1)Q_1(3) \\ Q_3(1)Q_1(2) - Q_3(2)Q_1(1) \end{bmatrix}.$$ 

Observe that, because the columns of $Q$ are orthonormal, we have $Q^{-1} = Q'$. Consequently, in y-space, using Eq. 2 under the transformation, Eq. (3), the trajectories of aircraft $A$ and $B$ are given by

$$y^A = \lambda Q'd^A$$

and

$$y^B = Q'(\bar{x}^B - \bar{x}^A) + \lambda Q'd^B,$$

for $0 \leq \lambda \leq 1$.

Now, consider a box of dimension $2\delta_1 \times 2\delta_2 \times 2\delta_3$ centered at aircraft $A$ and oriented along the $y$-axes, where, for example, $\delta = (\delta_1, \delta_2, \delta_3) = (S_1, S_2, S_3)$ if we are considering the standard separation criteria. Hence, as $\lambda$ varies from 0 to 1, and the box in the
y-space slides along the \( y_1 \)-axis, the (moving) aircraft (particle) \( B \) will lie in the box if and only if
\[
-\delta \leq y^B - y^A \leq \delta, \quad \text{i.e.,}
\]
\[
-\delta \leq Q'(\bar{x}^B - \bar{x}^A) + \lambda Q'(d^B - d^A) \leq \delta. \quad (6)
\]

The six inequities in Eq. 6 (two for each dimension) define simple inequalities in the single variable \( \lambda \), which, when intersected with \( 0 \leq \lambda \leq 1 \), will produce the interval \([\lambda_1, \lambda_2]\), where,
\[
0 \leq \lambda_1 \leq \lambda \leq \lambda_2 \leq 1, \quad (7)
\]
if this intersection is nonempty, or, otherwise, will indicate that no conflict (of type determined by \( \delta \)) occurs over this duration.

For computational efficiency, the above conflict analysis need only be conducted for flight pairs that are flying on altitudes that differ by less than or equal to a distance of \( S_3 \). Furthermore, because testing each distinct pair of flights for conflicts is computationally expensive, logical tests are first performed to eliminate pairs of flights that cannot conflict. For each flight \( i \) in sector \( s \), let \( I^s(i) \) denote the interval between the entering and exiting time for flight \( i \) in sector \( s \). Only flights that occupy \( s \) or the sectors neighboring \( s \) for a time interval overlapping \( I^s(i) \) could possibly conflict with \( i \). For each sector \( s \), a set of neighboring sectors is specified such that the only possible conflicts that can occur with a flight that occupies sector \( s \), are with respect to those flights that simultaneously occupy some sector in this set of neighbors. These neighboring sectors are found by constructing a rectangular box that encompasses \( s \) plus a buffer area such that, if a flight does not lie within this box, it would not conflict with a flight in \( s \) (see Sherali et al., 1998, for details). Potentially conflicting pairs of flights are then recorded for performing a more detailed conflict analysis during the intervals in which they may possibly conflict.

2.2 Conflict Geometry and an Aggregate Metric for Conflict Severity

Some conflict metrics used in previous studies include the Kip Smith Metric and the Laudeman Metric as described in Suchkov, Embt, and Colligan (1997). The Kip Smith Metric identifies separation as the single most important factor in estimating collision risk. It uses the number of aircraft, the distance between flights \( i \) and \( j \) at time \( t \) (not separated by altitude), and an empirical factor to establish a measure of workload. The Laudeman metric incorporates nine traffic factors, using 2-min time increments and a 20-min projection of future aircraft positions. This metric attempts to compartmentalize workload as a series of time-space counts.

In contrast, we propose two conflict measures in this study. The first is a classification scheme for recording a conflict with respect to each intruder \( B \) that conflicts with a given focal aircraft \( A \), and provides a measure of several aspects impacting the difficulty of conflict resolution by air traffic controllers. Given that \( B \) penetrates the shell of \( A \), and that \( \lambda_1 \) and \( \lambda_2 \) in Eq. 7 are well defined, we will classify the conflict as being of

\[
\text{Class}[k_1, k_2, \theta, \tau, d_{\text{min}}]_B \quad (8)
\]

where \( B \) represents the intruding aircraft, and where the different entities in Eq. 8 are determined as follows. First, for \( \lambda = \lambda_1 \), we find the dimension \( \rho \) equal to 1, 2, or 3, if it exists, for which the corresponding inequality in Eq. 6 is binding, breaking ties first in favor of a dimension that has a non-zero \( \lambda \)-coefficient in the corresponding inequality in Eq. 6, and, for continuing ties, we favor dimension 3 (vertical separation), then dimension 1 (in-trail separation), and last, dimension 2 (lateral separation). If no inequality is binding (whence we must have \( \lambda_1 = 0 \)), we use \( k_1 = 0 \). Otherwise, we use \( k_1 = \rho \) if the identified inequality in Eq. 6 for dimension \( \rho \) is a right-hand inequality, and \( k_1 = -\rho \) if this is a left-hand inequality. Hence, the first entity in Eq. 8 designates the entry point of the intruder \( B \) within the box for aircraft \( A \). If \( k_1 = 0 \), then the conflict has been continuing from the previous segment because \( B \) lies in the interior of the box. Otherwise, a positive (negative) value for \( k_1 \) indicates an entry via the face of the box that is orthogonal to the corresponding positive (negative) \( k_1 \)-axis, with ties handled according to the stated order. This order is based on the dimension for which a smaller separation is usually specified in practice in case the entry occurs on an edge (or a vertex) of the box. Similarly, \( k_2 \) is defined with respect to \( \lambda = \lambda_2 \) and designates the face of exit (with ties broken as above), and where \( k_2 \) equals 0 (whence \( \lambda_2 \) must be 1) if the intruder continues to lie in the interior of the box at the end of this duration segment. The entity \( \theta \) is a relative heading angle between the trajectories defined by \( d^A \) and \( d^B \) of aircraft \( A \) and \( B \). The duration of intrusion over this time segment is given by \( \tau = T(\lambda_2 - \lambda_1) \). Note that, for continuing consecutive segments of intrusion, the total duration of intrusion can be obtained by summing \( \tau \) for the class vectors spanning from \( [k_1 \neq 0, 0, \ldots]_B, \ldots, [0, 0, \ldots]_B \). Finally, \( d_{\text{min}} \) denotes the minimum distance achieved between aircraft \( A \) and \( B \) over this duration segment.
The second conflict measure proposed is an aggregate metric that is useful for providing an executive summary viewpoint of the overall nature and extent of conflicts. For this purpose, during the conflict analysis, three imaginary protective boxes are constructed around the primary aircraft. The first is the outer protective box used to determine the presence of a conflict based on standard separation criteria. The second is an intermediate box with each dimension measuring half that of the first. The third is a tight box measuring 500 ft in front of and behind the aircraft, 500 ft to the left and right of the aircraft, and 100 ft above and below the aircraft. The severity of a conflict is measured by placing each conflict into one of three possible severity classes depending on the smallest box pierced. A conflict falls into severity class 1 if the intruding aircraft pierces the outer protective box (but not the other two boxes), severity class 2 if it pierces the intermediate box (but not the inner box), and severity class 3 if it pierces the inner box. Note that the higher the level of severity, the more vulnerable the situation becomes when uncertainties in trajectory paths (not considered here) due to weather or pilot blunders are superimposed on the scenario.

The proposed aggregate metric is a vector describing the number and the average duration of conflicts that fall within each severity class. (The average durations are computed only for severity classes 1 and 2 because conflicts of severity class 3 are untenable and require no further quantification.) This metric is given by

\[ (N_1, L_1, N_2, L_2, N_3), \]

where \( N_k \) is the number of pairwise conflicting aircraft of severity (at most) \( k \), and where \( L_k \) is the average length of conflict durations for severity \( k \), given by the sum of the durations over all pairs of flights for which a conflict of severity \( k \) occurs divided by \( N_k \). In our computations in Section 3, we provide information regarding this aggregate metric. (The detailed classification scheme for each conflict is also computed by AEM, but is not reported here for the sake of brevity.)

3. MODEL APPLICATION

3.1 National Airspace Resource Investment
Model Scenarios

To test AOM and AEM, several FAA-developed airspace scenarios were used. These scenarios represent a natural progression from current conditions (wherein 5-7% of aircraft use the National Route Program in which pilots are allowed to follow direct origin to destination routes at certain altitudes), to three dimensional Free-Flight (scenarios using wind-optimized, cruise–climb trajectories). The wind-optimized trajectories use the information regarding wind vectors that are recorded at various national weather service stations located throughout the country. Given the wind velocities and directions, a discrete dynamic programming algorithm is used to calculate the most efficient route for an aircraft. Cruise–climb trajectories optimize the altitude at which an aircraft should be flying. Because an aircraft loses weight during the course of its flight, the optimal flying altitude slightly increases throughout the course of a flight. Cruise–climb (CC) trajectories determine this rate, and, accordingly, prescribe a route containing a series of periodic climbs (instead of a steady continuous climb).

The NAS traffic demand scenario database used in this study represents typical NAS conditions for five days of the year, and contains the 1996 Enhanced Traffic Management System traffic information. This data was used as our baseline case. Each alternative scenario or operational concept examined below, as defined in the NARIM program literature (CSSI, 1996), uses different wind patterns that capture seasonal variations in the jetstream. These scenarios were generated by CSSI using a combination of the future demand generator and an optimization model OPGEN, that prescribes flight trajectories between an origin and a destination airport using variable ATC rules, aircraft performance parameters, and wind conditions, while optimizing individual flight tracks above FL 150. Except for the prevailing jetstream and wind conditions, other more uncertain events such as storms and severe turbulence zones were ignored in this study. The optimization of routes is performed over the enroute (class A airspace) segments of the flights. The terminal airspace trajectory maintains a preferred arrival or departure pattern due to congestion, and this therefore precludes the use of optimal routes in this (class B) airspace.

Another important assumption made relates to the optimization mode used. Flights longer than 1000 nautical miles (nm) were fully optimized subject to the constraints of the corresponding concept of operations (e.g., wind-optimized routing, with hemispherical rules, which dictate that East–West flights fly at one of the levels FL 290, FL 330, FL 370, and so on, and North–South flights fly at one of the levels FL 310, FL 350, FL 390, and so on) (CSSI, 1996). Shorter flights, less than 1000 nm, were “straightened,” subject to detours due to special-use airspace constraints, and were placed on reduced vertical separation minimum (RVSM) altitudes or at some appropriate altitude above FL 290,
where flights need only be separated vertically by 1000 ft., as opposed to 2000 ft. (CSSI, 1996).

Three operational scenarios proposed by the FAA to research transition to the concept of Free-Flight were investigated in this study. The following paragraphs summarize the ATC rules and wind conditions considered for each of these NAS traffic demand scenarios. For each of these scenarios, AOM was first run to ascertain the sector occupancies for each flight. Using this information, AEM was then run to analyze each pair of potentially conflicting flight plans over FL 180 to determine the existence and nature of each conflict, as discussed before. This conflict analysis was not performed below FL 180, because this segment of the airspace is regulated separately by terminal radar approach controls in the vicinity of airports under specific takeoff and landing separation procedures that differ from enroute separation criteria.

Current National Airspace Concept of Operations

This scenario represents the aforementioned 1996 traffic conditions for NAS. The trajectories are based on the actual flight plans filed by the airlines. The analysis includes mostly fixed-route flight plans that use the high altitude airway system in the US, relying on ground-based navigational aids (NAVAIDS) such as Very High Frequency, and Omni-Directional Range instruments.

Wind-Optimized Profiles with a Reduced Vertical Separation Minimum

This scenario reflects the removal of reliance on the ground-based NAVAIDs. The flights in this scenario are wind-optimized, adopt the stated reduced vertical separation standard of 1000 ft., and are placed at altitudes governed by the following level designations (CSSI, 1996): Westbound Flight Levels, begin at FL 180 and the levels increment at intervals of 2000 ft.; Eastbound Flight Levels, begin at FL 190 and the levels increment at intervals of 2000 ft. These level designations thus effectively enforce that oncoming flights are always separated vertically by at least 1000 ft.

Wind-Optimized Profiles without Hemispherical Rules (Cruise–climb)

This scenario reflects a complete relaxation of the previous restrictions. The trajectories are not constrained by the ground-based navigational aids, or by enforced flight altitudes dictated by vertical separation standards. The profiles represent optimal three-dimensional trajectories in the enroute airspace, considering wind conditions and the CC strategy as described above.

Four air route traffic control centers covering the Florida Peninsula: the Miami (ZMA) and Jacksonville (ZJX) Centers, and a mainland section: the Indianapolis (ZID) and Atlanta (ZTL) Centers, were selected for the sake of illustration. Figures 6 and 7 illustrate the dimensions of the sector modules that comprise these centers. The analysis was carried out for a pair of centers at a time to assess the effects over a relatively large geographical area. The flight plans analyzed were extracted from the aforementioned NARIM concept of operations database, which contains 18,000 flight plans per day that cruise above FL 240 in the baseline year (1996). For the sake of illustration, and to maintain a homogeneous flight data structure that reflects a contiguous traffic pattern, we selected a set of 18,166 flights that occurred over the NAS over a 24-hour span. Out of this set, 4,294 flights intersected the ZID–ZTL centers, and 1,494 flights intersected the ZMA–ZJX centers. This same set of flight plans was then modified under RVSM and CC rules to facilitate compar-
isons between the baseline scenario and these alternative scenarios.

For each of the three scenarios (baseline, Free-Flight under RVSM, and Free-Flight under CC), we first ran AOM to ascertain the number of flights crossing each sector. Using the flow pattern during 15-minute intervals over each sector, we recorded a time series of the number of flights occupying each sector over these time intervals for each of the Free-Flight scenarios versus the baseline case. Next, we used AEM to determine the number of blind-conflicts that occur during vertical transitions and during level enroute flight segments for each sector region under each of the aforementioned three scenarios. These results are reported below along with the aggregate conflict metric given by Eq. 9. We also provide an estimate of the potential increase in airspace handling capacity under the two Free-Flight concept of operations, in comparison with the baseline case, due to a reduced workload stemming from fewer potential conflicts that require resolution.

3.2 Model Results

This section presents the outcomes of AOM and AEM under the stated new NAS operational concepts (i.e., RVSM and CC flight conditions). Traffic flow results are first presented to verify whether these operational changes using RVSM and CC rules produce significant variations in sector traffic flows. Conflict results are then presented in a subsequent subsection to assess the number of expected blind conflicts in the identified centers, and its ensuing effect on airspace-handling capacity.

3.2.1 Traffic Flow Patterns

Traffic flow patterns in an airspace sector are important from a collision risk point of view because they are predictive of the number of potential blind conflicts. Moreover, sector traffic volumes could also be used subsequently to model end-game dynamics between conflicting aircraft that include ATC and pilot blunders.

The stream of flight occupancy information for each sector over 15-minute time intervals under the baseline case was compared with that for each of the two Free-Flight scenarios. A Wilcoxon signed rank test (SNEDECOR and COCHRAN, 1980) was performed to validate whether the sum of the sector occupancy rank differences is equal to zero (assuming that the distribution of the differences in ranks is symmetric about 0). The level of significance used was 0.05 (i.e., there is a 5% likelihood of incorrectly concluding that the sum of the sector occupancy rank differences is not equal to zero). For those sectors whose occupancies were found to be dissimilar in the transition to the Free-Flight scenario as determined by this test, we also ascertained whether this dissimilarity was due to an increase or a decrease in the sector occupancy by comparing the average number of flights that occupy these sectors over the time intervals. Table I presents the results for this analysis. Note that there are several sectors whose traffic patterns are significantly affected by the RVSM and CC concepts of operation. Table I demonstrates that the centers located in the Florida Peninsula (ZMA and ZJX) show less variations in traffic flows across sectors under RVSM or CC versus the baseline case, than those in the mainland portion (ZTL and ZID) of the continental USA. This result was expected since flights in Florida are relatively well organized in a North-South direction. The conclusion that can be drawn here is that aircraft flight tracks are impacted more in a central enroute control center where there is more latitude in optimizing flight-plan trajectories laterally. For example, a
westbound flight whose original track in the baseline scenario crosses ZID, might take consideration of the prevailing jetstream by traveling further south (i.e., crossing ZTL instead of ZID). Furthermore, the redistribution of flights via either the RVSM or the CC operation tends to have an effect of decreasing the occupancies of more sectors than the number of sectors for which an increase is observed.

To provide further information, Figure 8 displays certain statistics regarding the number of flights occupying each sector in the ZID and ZTL centers over 100-minute intervals for the baseline and the RVSM scenarios. A relatively larger time interval was selected to examine a more smoothed out variation in the flow pattern than is evident for the 15-minute interval time series. The mean number of flights occupying each sector over these 100-minute time intervals for the baseline case was plotted above the zero-line on the vertical axis, whereas the absolute differences in the mean number of flights between the baseline and RVSM scenarios were plotted below this line. This figure exhibits a moderate change in mean sector occupancies resulting from the Free-Flight scenario. Figure 9 displays the standard deviation in the number of flights occupying each sector over these time intervals for the baseline and the RVSM scenarios. From this plot, we see that flights occupying the ZID–ZTL centers are relatively more uniformly distributed under the RVSM scenario than under the baseline scenario for 38 of the total of 90 sectors, with a comparable variability observed for three sectors. Similar results were obtained while comparing the baseline and CC scenarios, and for the ZMA–ZJX centers. We also compared the RVSM and CC scenarios, and discovered that the differences in mean sector occupancies and variances were relatively small.

The results from this investigation suggest that small to medium changes in sector occupancies are observed with the transition to Free-Flight. The changes are highly varied because aircraft trajectories differ substantially (both laterally and vertically) when flights use wind-optimized tracks. All flights are contained within one of four enroute traffic control centers.

### 3.2.2 Conflict Results

The foregoing three concepts of operations were applied to the above set of flights traversing the four centers under consideration, and the number of conflicts detected by AEM in the enroute airspace and during vertical transitions were recorded and analyzed. The results of this analysis are presented in Table II for the Florida Peninsula centers ZMA and ZJX, and in Table III for the mainland section centers ZID and ZTL. These tables display the number
of conflicts at each level of severity, and the average duration of the conflicts at the severity levels 1 and 2 (see Eq. 9), while the aircraft are in vertical transitions (Column 2), and during the level portions of the enroute flights called enroute flight segments (Column 3). Vertical transition conflicts are defined as conflicts that occur when at least one of the aircraft is executing a vertical change above FL 180. The last row of each table records the total number of conflicts and the overall average duration of conflicts having severity levels 1 and 2, for each of the cases of vertical transitions and enroute flight segments.

Intuitively, the expectation might be that, under Free-Flight operations, the number of blind-conflict encounters would increase for a given traffic density because of the lack of controls in managing the flight trajectories. On the contrary, our results predict a significant decrease in potential conflicts as seen in Tables II and III, and summarized in Table IV for the case of enroute segment conflicts. The reason for this is that the flight plans for the baseline case follow certain standard way-point-based trajectories that happen to represent restricted airspace corridors, whereas the unconstrained trajectories under the various Free-Flight concepts are more dispersed over the airspace covering the region of concern. This reduction in congestion results in fewer potential conflicting encounters between pairs of aircraft.

Now, assuming that the number of (enroute) conflicts is proportional to the square of the number of flights, we can roughly estimate the increase in (enroute) airspace capacity that is implied by the reduction in the number of conflicts from the baseline scenario for each of the Free-Flight scenarios RVSM and CC (see Magill, 1998). For example, if \( c_1 \) and \( c_2 > c_1 \) are, respectively, the number of conflicts under a Free-Flight and the baseline scenario for a certain sector region, the percent increase in the number of flights under the Free-Flight scenarios that would give the same number of estimated conflicts as under the baseline case is given by \( \frac{\sqrt{c_2} - \sqrt{c_1}}{\sqrt{c_1}} \times 100\% \). This quantity reflects a percentage increase in airspace-handling capacity for the same expected conflict-intervention workload, and is computed for each pair of centers in Table IV, under each of the Free-Flight concepts RVSM and CC.

Naturally, this is only a rough analysis, and further research is needed to assess the validity of this increased capacity.

Some would argue that, due to an apparent reduction in the number of conflicts under RVSM and CC conditions, ATC controllers would experience less workload, and thus the system might be safer than under the baseline conditions. This notion needs to be further investigated, given that workload is not a simple linear function of the number of flights traversing a sector or the number of conflicts that require intervention. It also depends upon other complexities such as sector geometry, flight path and

| TABLE II  
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<tr>
<th>ZMA and ZJX ARTCC Conflict Statistics</th>
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<tr>
<td><strong>Blind Collision Type</strong></td>
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<td><strong>Number of Conflicts</strong></td>
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<td><strong>Baseline</strong></td>
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<td>Severity 1</td>
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<td>Severity 3</td>
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<td>Total</td>
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<td><strong>RVSM</strong></td>
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<td>Severity 1</td>
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<td>Severity 2</td>
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<td>Severity 3</td>
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<td>Total</td>
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<tr>
<td><strong>Cruise–Climb</strong></td>
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<td>Severity 1</td>
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<td>Total</td>
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| TABLE III  
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<tr>
<th>ZID and ZTL ARTCC Conflict Statistics</th>
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<tr>
<td><strong>Blind Collision Type</strong></td>
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<td><strong>Number of Conflicts</strong></td>
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<td><strong>Baseline</strong></td>
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<td><strong>RVSM</strong></td>
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| TABLE IV  
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<th>Summary of Conflict Statistics and Capacity Enhancements</th>
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<td><strong>Sector Region</strong></td>
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<td>ZMA and ZJX</td>
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<td>ZID and ZTL</td>
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conflict geometries, human reliability, situational awareness, and available automation tools. The point here is that, from the individual collision risk assessment viewpoint, all else being equal, a blunder during RVSM or CC might be more likely to cause a midair collision than under baseline conditions due to reduced margins of vertical separation and due to limitations of the human controller in spatially separating incoherent traffic. Assessing the probabilities of such failures occurring in a more automated environment is a challenging issue that warrants further investigation.

4. CONCLUSIONS

This paper focuses on the development and application of two models: an AOM and an AEM, designed to, respectively, predict traffic flows across defined volumes of airspace (sectors), and to predict the number of potential blind conflicts if all flight plans are executed without controller or pilot intervention. New concepts and metrics for classifying the geometry and severity of conflicts are described. The models developed have been coded in MATLAB (Mathworks, Inc., 1997), a general engineering language. This facilitates their execution on any computer platform (PCs, PowerPC Macs and UNIX workstations) without modifications. Using real data provided by the FAA, preliminary analyses of blind conflicts expected to affect the NAS system in the near future under two Free-Flight operational concepts: RVSM and CC are conducted. The results provide insights into the potential advantages, noting the stated points of caution, that might accrue in transitioning to the Free-Flight scenarios.

Although this study provides a first-order approximation analysis of the level of conflict exposure in a particular sector or center, it does not provide a measure of collision risk in the true sense. Further investigation of the end-game ATC and pilot dynamics (including aircraft navigational accuracy capabilities) is needed to truly quantify collision risk.

Several conclusions regarding the effects of the analyzed Free-Flight operational concepts can be derived from this study. First, there would be small to moderate variations in traffic flow patterns across various ARTCC center sectors in NAS, depending upon their geographical location. Second, the number of potential conflicts in the enroute airspace system would decrease with the introduction of Free-Flight operations if reduced vertical separation criteria are allowed. The number of blind conflicts expected under RVSM and CC modes of operation are of the same order of magnitude, although it is not clear how ATCs would react to potential conflicts between two or more aircraft operating in a CC scenario, and what would be the consequent effect on collision risk. Third, vertical transition conflict durations under RVSM and CC scenarios are generally expected to be shorter due to the smaller vertical separation criteria. Finally, enroute conflict durations (i.e., durations for coplanar conflicts) appear to vary significantly.

It is recommended that future research should perform a similar analysis as conducted in this paper using NAS scenarios for the years 2005 and 2015 which were recently developed by the FAA/CSSI. Also, a more comprehensive study of the NAS behavior should be undertaken to assess the effects of geographical and procedural differences across the various ARTCC centers. In our study, only four of twenty centers were analyzed. The models developed can process all NAS data at the expense of a more computationally intensive study.

AEM can also be executed using various detection envelopes to assess differences in conflict rates under various vertical, in-trail, and lateral separation criteria. To quantify collision risk under ATC and pilot intervention, a detailed investigation of controller, pilot, and aircraft dynamics should be undertaken. One possible approach is to enhance the AEM model by introducing end-game dynamics using causal theory, dynamic fault-tree analysis, or other suitable techniques, accompanied by mathematical models of the complex human-in-the-loop interactions in response to a potential conflict. For instance, there is a critical need to collect information on pilot and airline operational practices, and on ATC responses and separation maneuvers under the various new NAS operational concepts. This is viewed as an important step to quantify the reliability of human controllers in an intervention model framework. The models developed in this study offer an essential ingredient and first step toward undertaking such investigations.

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REFERENCES


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