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Analysis of the Aircraft to Aircraft Conflict Properties in the National Airspace System

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The primary function of administering the United States' National Airspace System (NAS) is the air traffic controller task of actively monitoring assigned aircraft and resolving the conflicts (i.e. losses of minimum separations between aircraft) anticipated some time in the future. To mitigate the safety risks of increased traffic growth and effectively designing automation to aid in the separation management task, knowledge of the characteristics or properties of the conflicts is required. This paper reports on a comprehensive study that has examined these properties by collecting traffic data from all 20 NAS en route centers, developing software models to determine these events, implementing experimental design techniques to calibrate them, validating the models by comparing to advanced operational systems, and presenting detailed graphical and statistical analysis of the results.

I. Introduction

In the United States, the overall system of managing and controlling air traffic is known as the National Airspace System (NAS), which is administered by the Federal Aviation Administration (FAA). Detailed procedures involving restrictions on routing, speeds, and altitudes are an integral part of the NAS. These restrictions severely reduce the amount of aircraft traffic that NAS can accommodate, yet are needed to ensure the high level of safety required. At the heart of these operations is the human air traffic controller who must synthesize many pieces of timely information including radar surveillance information and flight data. Their fundamental responsibility is to ensure the safety of the aircraft flying within their regions of airspace in the most efficient means possible. To accomplish this, air traffic controllers actively monitor their aircraft and then resolve any conflicts (i.e., loss of minimum separation between aircraft or restricted airspace) predicted some time into the future. Furthermore, these resolutions are administered by air traffic controller voice instructions via radio transmissions to the aircraft.

In the current system, there are automation systems that aid the air traffic controller mainly in the monitoring part of the task such as the ground based tactical and strategic conflict probes. In the en route centers, typically managing the aircraft above 18,000 feet, the Host Computer System's (HCS) Conflict Alert function provides tactical alerts. The upgrade to the HCS, still under development, called the En Route Automation Modernization (ERAM), replaces Conflict Alert with several categories of alerts with the basic function requiring a minimum of 75 seconds warning. The User Request Evaluation Tool (URET), developed by MITRE Corporation's Center for Advanced Aviation System Development, is an example of a strategic conflict probe in operation in the en route centers. It predicts conflicts up to 20 minutes in the future with typically a minimum warning of five minutes.

Even with the aid of ground-based conflict probes, the task of separating aircraft will become increasingly difficult, since most air traffic service providers in the United States and Europe anticipate significant growth in air traffic. The growth is expected to out pace the capacity limits of the aviation systems, resulting in greater congestion and inefficiency. The interagency Joint Development Planning Office (JPDO) in the United States foresees a traffic demand increase by 2025 up to three times the number of flights of today's traffic.[1] Given the need for enhanced safety and efficiency, broad categories of advances in ground and airborne automation are required. The JDPO, as established in their charter under the "Vision-100" legislation (Public Law 108-176) signed by President G. W. Bush in December 2003, has mandated a next generation operational concept of the NAS for 2025.[1] This next generation

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NAS envisions a trajectory based separation management system that requires precise management of the aircraft's current and future position. The separation function of today, relying heavily on the cognitive skills of the air traffic controller to visualize aircraft trajectories on the radar display and issue resolutions via voice instructions to pilots, will be replaced by a distributed system of separation management components, implementing performance-based separation standards. This future system will rely heavily on enhanced automation with conflict resolutions that are communicated digitally between air and ground and between aircraft. Thus, the technical challenges are many.

Besides the advances in navigation and surveillance, wake-vortex modeling and sensing, and implementation of digital data transmission infrastructures that will support reductions in the separation standards, more study is required of the conflict events themselves to determine where the automation systems will fail and how to mitigate those risks. As early as 1997, researchers in Europe examined the relationship between trajectory predictability and the basic miss and false errors of detecting these conflicts.[2] During the same time period, researchers from the National Aeronautics and Space Administration (NASA) developed complex models estimating the probability that the conflict detected actually occurs based on knowledge of geometry and trajectory accuracy.[3] Yet other European researchers, building on the previous NASA work, explored the relationship of the geometric variables (e.g. encounter angle or speed differential between aircraft) to the uncertainty of the predictions.[4] Since the focus of these early works was on developing models for estimating the conflict probability or impact of the prediction errors, there was only indirect information on the actual operational characteristics of the conflict events themselves, referred to as the *conflict properties*. With knowledge of the distribution of these properties for a given airspace and traffic situation, better assessments can be made to determine the performance of an automation system; in particular those envisioned for the JPDO's next generation NAS (a.k.a. NextGen). The objective of this paper is to expand on the previous research and investigate the conflict properties of the current NAS in the United States.

II. Previous Research on Conflict Properties

Research eventually was conducted directly on the properties of aircraft-to-aircraft conflicts. The most noteworthy began in 2001 when NASA researchers published a paper, cited in Ref. 5, comparing the conflict properties of two operational environments of the NAS. The first representing the current structured flights of the NAS, flying on defined routes and adhering to typical air traffic control altitude and speed restrictions, while the second representing a future free routing aviation system where flights flew on their great circle routes from origin to destination airport. The study included traffic for the entire NAS of flights above 18,000 feet, approximating Class A en route airspace. It utilized NASA's Future ATM Concepts Evaluation Tool (FACET) to generate aircraft trajectories based on 24 hours of flight plan data collected from the Enhanced Traffic Management System (ETMS) in March 2001. It modeled over 37,000 flights with zero winds and standard temperatures. Various conflict properties were compared between the two traffic configurations, showing that the free structured environment had distinct advantages in lowering the overall conflict counts and minimizing the interactions of these conflicts.

In 2004, European researchers published a similar paper, cited in Ref. 6, describing the conflict properties from altitudes 6000 feet and above in the European Civil Aviation Conference (ECAC) airspace. It included a simulation of ECAC traffic covering an entire 24 hour period. It utilized the EUROCONTROL Experimental Center's (EEC) Complexity Light Analyzer (COLA) tool that simulated the aircraft trajectories. The simulated flight trajectories were based on recorded air traffic operations from June 13, 2003 and extracted from the European CFMU (Central Flow Management Unit) and corrected with ETFMS (Enhanced Tactical Flow Management System) surveillance data with three minute update rates. The flights were simulated to fly on the European routes, adhering to the altitude and speed restrictions, much like the structured simulation in the earlier NAS study. A key finding reported in this study was that most of the conflicts did not occur when both aircraft were in level flight. Only 9% of the conflicts were with level aircraft below flight level (FL) 180 and 18% above. Thus, most European predicted conflicts occurred when one or both flights were vertically transitioning. It reported that the distribution in conflict encounter angles and speeds differed depending on vertical phase of flight and altitude. Many of the conflicts at the lower flight levels were in-trail conflicts with high speed variances. Conflicts at higher altitudes were more equally distributed in encounter angle and speed ratios close to one.

Besides the primary difference in airspace studied, there were three basic differences between these two studies:

(1) the European study simulated aircraft from FL60 and above where the NAS study started at FL180,
(2) the European study used the more contemporary vertical separation standard of 1000 feet[§],
(3) and both studies reported on a largely different set of conflict properties.

[§] U.S. vertical separation is 1000 feet below FL290 and 2000 above. In 2005, certified aircraft began using 1000 feet above FL290, called Reduced Vertical Separation Minimum (RVSM). Europe already applied RVSM in 2004.

Table 1: Comparison of United States and Europe Reported Conflict Properties[5-6]

#	Conflict Property	NASA Result on NAS[5] (only >FL180; here only structured)	EUROCONTROL Result on ECAC[6] (>FL60 unless specified; structured)
1	Vertical phase of flight during the conflict	L-L=75%, L-NL=20%, and NL-NL=8% for L=level and NL=non-level	Divided into all six combos of cruise, climb, or descent; translated for >FL180: L-L=18%, L-NL=51%, and NL-NL=31%
2	Encounter angle	Percent of conflicts bins of 0-60, 60-120, and 120-180 degrees, 53%, 19%, and 28%, respectively	Categories in-trail 0-15, cross 15-165, and opposite 165-180 degrees by vert. phase; for all 34%, 50%, and 16%, respectively
3	Encounter angle by vertical phase of flight categories	None	Vertical phases, enc angle by log and actual number of conflicts; showed peaks at extreme angles; evenly distributed most phases, except climb-descent peaked near 180 degrees
4	Encounter angle by altitude band and vertical phase of flights	None	All vertical phases with percent of conflicts per altitude per encounter angle category; then six more one per vertical phase combo
5	Encounter speed difference by altitude band and encounter angle	None	Speed ratio (v1/v2) 0-3 by altitude with three encounter angle categories per altitude; lower altitudes have higher speed differences and reaches 1.1 asymptote at higher altitudes
6	Number of conflicts by number of aircraft	Conflict count per unit time by number of aircraft; fit quadratic yet near linear	None
7	Conflict duration	Percent of conflicts with bins of <1, 1-2, 2-5, 5-10, $\geq$10 minutes; mean 2.9 min	None
8	Distribution of intrusion[**]	Percent of conflicts versus horizontal, vertical, and combined intrusion parameters; 0.75 mean total	None
9	Number of conflicts encountered by an aircraft	Percent of conflicting aircraft by number of conflicts encountered by an aircraft; bins 1, 2, 3, $\geq$4	None
10	Number of conflicts per unit time	Instantaneous number of conflicts per unit time, 0-24 hours, peaks at 65 conflicts	None
11	Temporal conflict interaction	Percent of conflicts by categories of time overlap; none, weak, and strong[††]; 84%, 10%, 6%, respectively	None
12	Average aircraft proximities	None	Average number of aircraft in specified airspaces within radii 10, 25, 40, or 70nm

[**] Intrusion parameter is ratio between zero and one indicating the minimum separation the aircraft pair achieved in the duration of the conflict. A ratio of one indicates a collision between the two aircraft and zero indicates exactly at the legal separation standard, thus not a conflict.

[††] Temporal conflict interaction is defined as the degree of time relationship between separate conflicts where one or both aircraft are common. None indicates no time relationship between conflicts, while strong indicates actual time overlap. Weak indicates the conflicts are not predicted to overlap but are near in time.

For the altitude ranges covered, the European study did stratify their metrics for below and above FL180, so both studies are comparable in that respect. For the difference in separation standards, the reader must qualify any comparisons of the two studies based on this difference, particularly related to minimum vertical separation at altitudes above FL290. Lastly, some of the conflict properties were comparable, and others were not, and in most cases the two studies defined different properties altogether. Table 1 summarizes the list of properties investigated in both studies and aligns those that have reasonably matching definitions.

For the first conflict property listed in Table 1, the distribution of encounter angle reported for the two airspaces were quite different. Most conflicts in the United States airspace were among level aircraft and for the European airspace it was the opposite. This is the first indication that the air traffic in these two sets of airspaces is very different. This is not surprising based on Ref. 7, where the United States and European airports and airspace were compared. Although many similarities were reported, several European centers were compared to more generally congested United States centers in the Northeast, like New York and Chicago. In one example, it was indicated that the London Center in Europe was comparable to New York Center in the United States in quantity of traffic, type of traffic, and average transit time. Keeping these differences in mind, this paper will later explore the distribution of conflict properties by center and geographic region in the United States.

For encounter angle, the categories and their ranges were somewhat different making it difficult to compare the two systems being reported on. However, both Ref. 5 and Ref. 6 illustrated the importance of examining encounter angle and classification of in-trail, opposing, and crossing angles. Ref. 6 spent considerable effort reporting on encounter angle correlated with other properties such as vertical phase of flight, altitude, and speed differential. As originally described in Ref. 4 and again in Ref. 6, an important mathematical relationship was referred to between the speed differential between aircraft in conflict and encounter angle.

There were several metrics not examined in the European study. Conflict duration, number of conflicts as a function of aircraft flying, temporal interactions, and intrusion parameters are all examples. An additional metric was reported in the European study not provided in the United States version. It reported on the average proximity counts of other aircraft for conflicting aircraft for high conflict rate centers. Although not exactly the same, it is similar to the temporal interactions developed in the United States paper only.

Both studies provided compelling evidence that the aircraft-to-aircraft conflict properties had descriptive value of the airspace and traffic it was reported on, and was useful for future automation designers. It also showed the many gaps that existed between the two studies, leaving plenty to build upon in collecting new data in the United States, and applying a superset to capture the current conflict properties of the NAS under cotemporary RVSM rules.

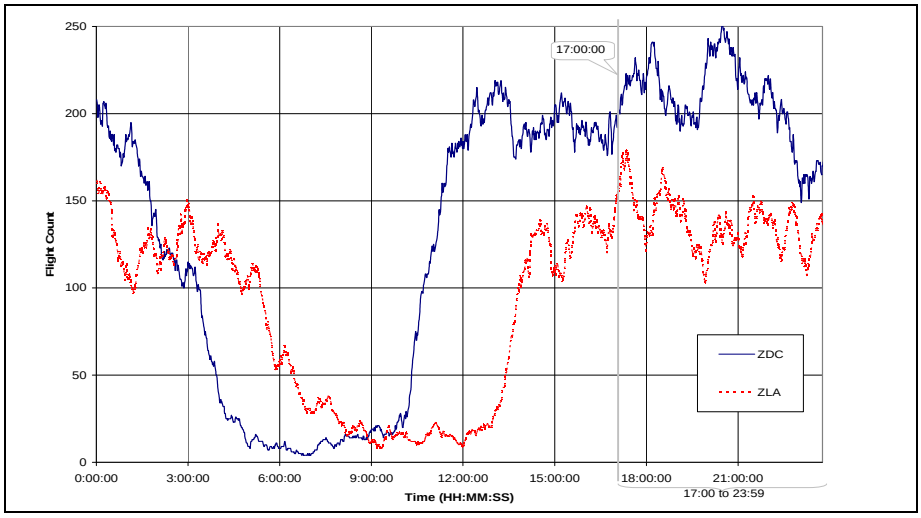

Figure 1: Data Collection Time Selection

III. Air Traffic Data Collection and Preparation

Twenty four hours of air traffic messages, amounting to almost 40,000 flights, and associated adaptation (i.e. detailed definitions of airspace boundaries and fix locations for expanding the flight plans) were collected on April 3, 2008 for all twenty en route Air Route Traffic Control Centers (ARTCCs) within the continental United States. The air traffic messages were retrieved from the Host Air Traffic Management Data Distribution System (HADDS).

These messages record each ARTCC's air traffic control clearances and surveillance track positions. Next, the messages are parsed and planned routes are expanded from the flight plan amendments into a series of geographic positions. These expanded routes and track positions are the main input data source for generation of aircraft trajectories and later conflict predictions. To perform these predictions, a set of complex software tools were developed, then described in detail in Section IV. The software is calibrated using experimental design techniques, described in detail in Section V. Later in Section VI, the predictions are validated by comparing them to the existing performance of operational systems like URET and ERAM. Finally in Section VII and concluded in Section VIII, a series of charts estimating the various conflict properties is illustrated and noticeable trends discussed.

Only a subset of the full twenty four hours of traffic recording was determined to be necessary for this study. Fig. 1 illustrates this by plotting the quantity of flights within two ARTCCs, Los Angeles (ZLA) on the West coast and Washington D.C. (ZDC) on the East coast. They cover the extremes in range of time zones and illustrate the two daily peaks and valleys in traffic loading. As a result, only the traffic messages recorded after 17:00:00 UTC and less than 23:59:59 was utilized for this study. This interval is highlighted in Fig. 1.

Unfortunately, the daily traffic peak is only part of the story when selecting the data to include in the study. NAS flight plans by definition precede radar track reports in operations. Consequently, all track reports that happen to precede their associated flight plans were discarded, reflecting an artifact of capturing live field recordings. Since our later trajectory predictions require both flight plans and radar track positions to make valid conflict notifications, a detailed analysis was performed to determine the required ramp up time to ensure no flight data is truncated. Fig. 2 illustrates the difference between the full flight count per unit time and the flight count that had been truncated by requiring flight plans to precede track data. A sample of four ARTCCs from the various time zones is selected, including ZLA and ZDC, same as the full data time selection discussed previously, and additionally Chicago (ZAU) and Denver (ZDV). Thus, the required ramp up period for all four selected ARTCCs to converge to a difference close to zero is determined to be 18:40 UTC or 67200 seconds in the day. This is illustrated graphically in Fig. 2.

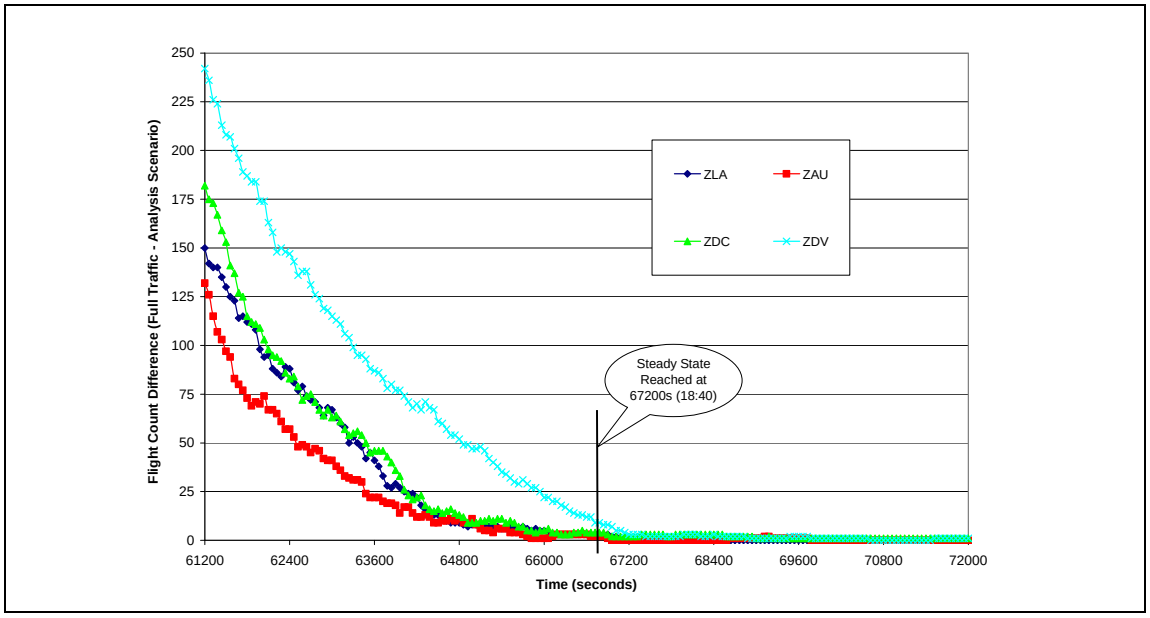

Figure 2: Determination of Analysis Steady State Time

IV. Model Description

This section describes the two sub-systems required to model and predict the conflict notifications this paper is reporting on. The first sub-system is the forecast or prediction of the four dimensional path of the aircraft in the future. We refer to this process as the trajectory predictor (TP). The trajectory predictions generated by the TP are supplied to another software tool responsible for generating the conflict notifications themselves, referred to as the Trajectory Conflict Probe (TrajCP). This is described in detail in the following two sub-sections, TP model and then TrajCP, respectively.

A. Trajectory Prediction Model

In the current air transportation system, automated systems aid air traffic controllers in monitoring air traffic in order to maintain minimum separation standards between aircraft. These automated systems provide this service by predicting aircraft flight paths, in order to foretell potential conflicts or provide other air traffic services. For this study, a laboratory TP model was developed. In comparison to operational TPs (i.e. URET or ERAM), this TP model is simplistic in nature, designed specifically for an experimental or analytical environment.

1. Trajectory Predictor Structure

A common trajectory predictor structure was presented in Ref. 8 by an international group of TP designers. Figure 3 illustrates the common elements of this generic operational TP. For this study, we focus on the Trajectory Engine (TE) module, and a selected set of supporting modules. The grayed elements in Fig. 3 represent the modification of the generic TP structure to fit into our experimental TP environment. Some functions and input of the generic TP structure (i.e. trajectory update process, aircraft performance library, and constraint specifications) were not required. These functions may be critical in an operational context but are not required for this study.

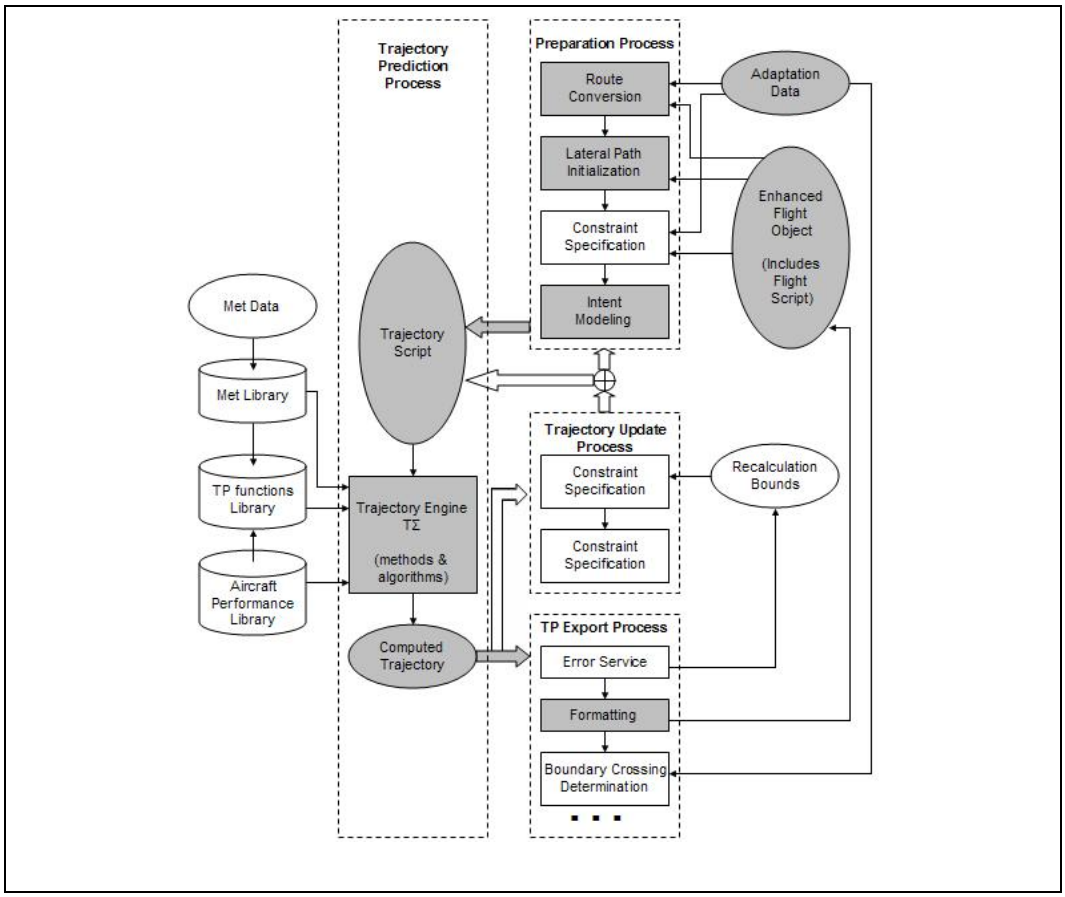

Figure 3: Application of Generic Trajectory Predictor (adapted from Ref. 8)

The trajectories predicted by the TE are the main source for defining and characterizing the aircraft-to-aircraft conflict events needed for this study. The larger application that drives the TE and other TP modules to detect conflicts will be described in Section IV.B. Only a sub-set of modules derived from Fig. 3's generalized functions were implemented. They include:

- *Enhanced Flight Object module* - the NAS data source for the TP presently provided through HADDS.
- *Adaptation Data module* – where the airspace sector configurations and lateral route fixes are defined.
- *Route Conversion module* – translates a route, a series of airways and waypoints, into a series of latitude and longitude points.
- *Lateral Path Initialization module* – determines the path from current position to the route.
- *Intent Modeling module* – provides how aircraft operations (e.g. vertical climbs) will be modeled.

- *Trajectory Script module* – describes how an aircraft will be operated, for the purposes of trajectory prediction, including tactical and procedural ATC constraints.
- *Trajectory Engine* – described, in detail, in the next section, Section IV.A.2

2. Trajectory Engine Algorithm

The core module in a TP is the trajectory engine (TE). The TE is the hub of the trajectory prediction process. It is where the aircraft characteristics, weather data, aircraft intent data, airspace procedures, and other relevant information are synthesized to generate the predicted aircraft flight path. The TE developed for this study utilizes the current aircraft's state vector properties and flight plan relationship in order to build a simple 4-D trajectory.

In the long term, an aircraft that has deviated from its flight plan is expected to rejoin the flight plan's route, referred to as the converted route, unless there is an amendment changing this planned path. In the near term the aircraft may fly away from its converted route, fly parallel to, or rejoin the route at a downstream fix (i.e. a designated position on the route). The TE choice on whether to utilize the flight plan completely, whether to never use the flight plan, or when to rejoin the route later is dependent on the aircraft's current reference to the route. The process begins by determining whether or not the aircraft is on its route. The geometry of an aircraft's relationship to the converted route is illustrated in Fig. 4. This relationship was first explored in detail in Ref. 9.

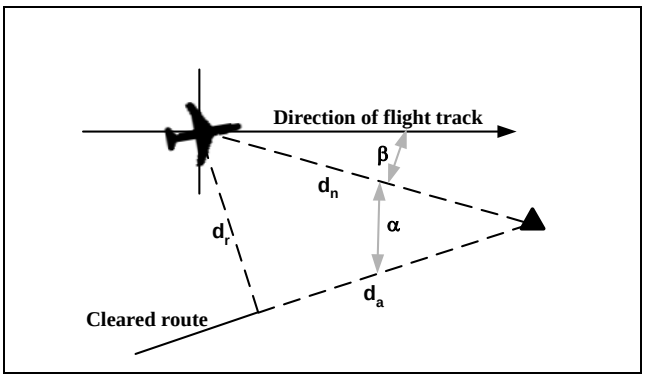

Figure 4: Geometry of Route Deviation (from Ref. 9)

The algorithm follows the logic in Fig. 5 and uses two calculated parameters from Fig. 4's route deviation geometry: β and d_r. First, the aircraft is projected onto the route and the distance is calculated. This distance is illustrated in Fig. 4 as d_r. If this distance is less than a small threshold value D_1 (e.g. 0.5 nautical mile), it is assumed that the aircraft is flying on its route. Thus, a trajectory is built starting at the projected position and follows along the converted route some time horizon into the future. If the distance is greater than a large threshold D_2 (e.g. 1.5 nautical miles), it is assumed that the aircraft is no longer flying its route. In this case, the state vector method is applied, which assumes the aircraft will continue on its current heading at its current velocity. Estimates of the current speed, heading, and rate of climb are made from the surveillance track data. These estimates are used to generate a linear trajectory of the aircraft for the immediate future. The horizontal and vertical accelerations are assumed to be zero. If the aircraft is climbing or descending, it is predicted to level off at its cleared altitude. If this linear trajectory intersects the route at some downstream location some time before the end time horizon (i.e. look-ahead time window) or before the converted route ends, it is assumed that from the point of intersection the aircraft will follow its route.

If the distance of the aircraft from its route is between the two threshold distances, the angle between the aircraft heading and a direct path to the next fix on the route is calculated. This angle, β, is illustrated in Fig. 4. If β is less than a threshold value P_1 (e.g. 30 degrees) the aircraft is headed back, thus assumed to be flying on its route. It then results in a trajectory following its route. If β is greater than the threshold, the state vector prediction is used to generate the trajectory. As described above, if this linear trajectory intersects the route downstream, it is assumed that from the point of intersection the aircraft will follow its route as well.

In summary, if the aircraft is close to its flight plan route, it will follow its route. If the aircraft is far away from its route, it will follow a state vector projection and if this prediction intersects the route it will then follow the route for the remaining time horizon. Furthermore, the time horizon into the future or look-ahead time of the trajectory prediction, the time step of trajectory positions along the trajectory, and frequency the trajectory is generated are all

parameters supplied to the TP. For this study, a 20-minute look-ahead time, a 10-second time step, and 10-second trajectory generation frequency were used.

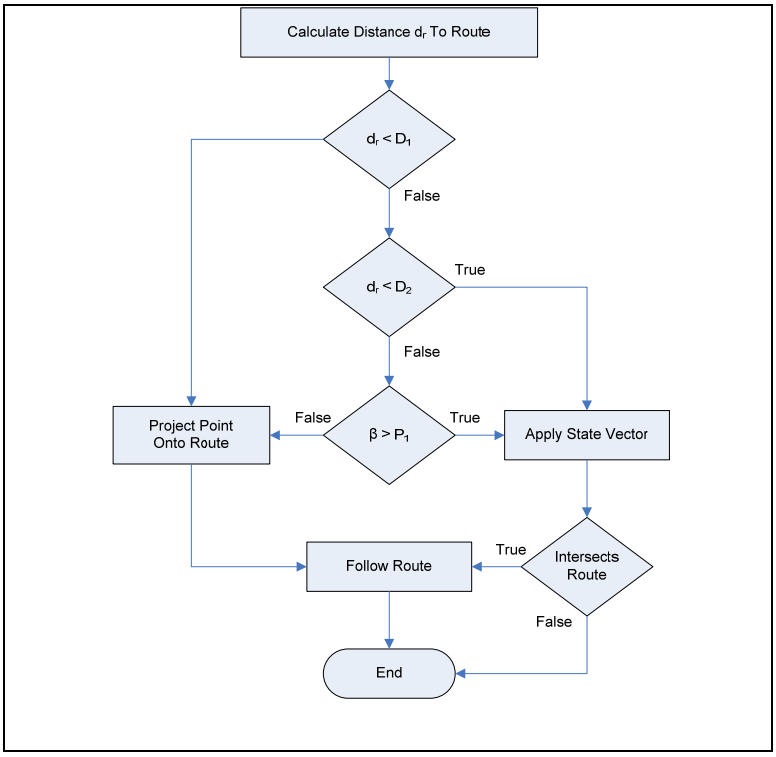

Figure 5: Trajectory Engine Logic Flow

B. Trajectory Conflict Probe Model

The ideal method envisioned in collecting information on the conflicts air traffic controllers solve would be to sit with every controller and record these resolutions as they occur across the NAS. However, this would be infeasible with the literally thousands of controllers and even more events occurring every hour of the day geographically dispersed across the country. A more practical method is needed. In order to quantify the properties of the conflicts within the NAS effectively, the TP described in previous Section IV.A was employed to generate a trajectory prediction at every surveillance track position. A software tool was developed to implement this methodology. The application is called the Trajectory Conflict Probe (TrajCP). The input to TrajCP is a recorded air traffic data scenario, which is itself a collection of air traffic data parsed from messages recorded in HADDS for many flights over a certain period of time. The air traffic scenario is pre-processed and stored in a collection of relational databases. TrajCP outputs predicted conflicts and property data to a database table that can be analyzed by external tools. TrajCP is a simplified version of the operational CPT; however, TrajCP has been validated by comparing it to operational CPT results. The validation of TrajCP will be discussed later in Section VI.

A conflict event is the loss of minimum separation between two aircraft predicted trajectories. The algorithm TrajCP uses to detect conflicts is illustrated in Fig. 6. A conflict event occurs between two aircraft; therefore TrajCP begins processing by organizing the air traffic scenario by sets of aircraft pairs. The algorithm for detecting conflicts is a function of the number of aircraft pairs, which is in turn a function of the number of aircraft squared supplied by the air traffic scenario. As a result, the quantity of aircraft pairs to process can increase dramatically when traffic loading increases or the scenario duration is extended. Thus, efficient filtering methods are needed.

For each aircraft pair, TrajCP first examines if the time and spatial gross filtering conditions are passed. In order to pass the time gross filtering condition, the aircraft pair must have time overlap. Next, in order to pass the spatial gross filtering condition, the bounding boxes of the *X, Y,* and *Z* dimensions must be within a specified distance (typically 35 nautical miles and 3000 feet). If these two conditions are satisfied, then the aircraft pair is processed for potential conflicts, otherwise the aircraft pair is skipped. The failure of the gross filtering conditions allow a significant number of aircraft pairs produced to be excluded, since only aircraft pairs that have time commonality

and fly at least near each other are processed further[‡‡]. Next, if the aircraft pair passed the flight gross filtering, the TP generates two trajectories, the subject and object trajectory, for each aircraft in the pair, respectively. If the TP successfully generated both trajectories and the two trajectories passed the trajectory spatial gross filtering condition[§§], then TrajCP considers this to be the situation where a potential conflict could exist. A potential conflict is detected when the path of the predicted trajectories breaks the minimum separation thresholds. These minimum separations are configurable as input into TrajCP. For this study, standard legal separation distances were used (5 nautical miles horizontally and 1000 or 2000 feet vertically depending if the aircraft were RVSM equipped).

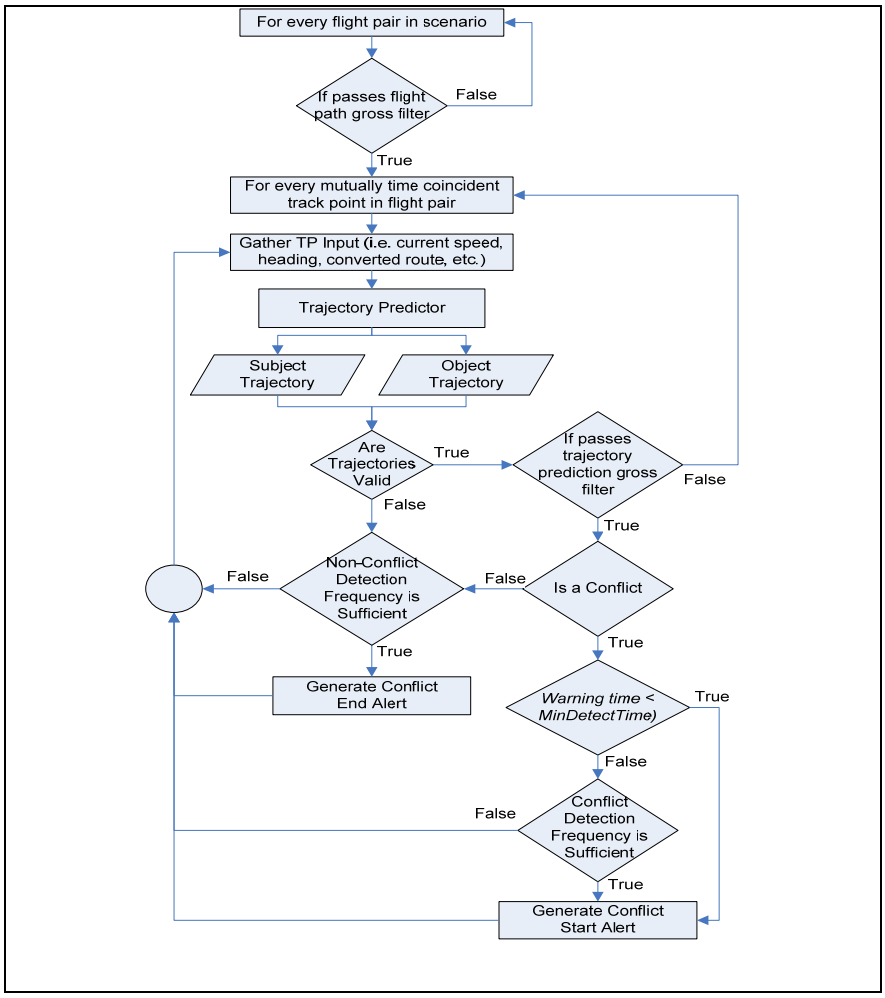

Figure 6: Flowchart of the Trajectory Conflict Probe algorithm

Once a conflict is detected, if the predicted warning time is within a user-specified parameter the conflict is recorded immediately as a conflict notification. The warning time is the amount of time from the detection of the conflict until the predicted conflict start time. If the detected conflict is predicted to begin outside the minimum predicted warning time (*MinDetectTime)* threshold, then before recording it as a conflict notification the conflict detection frequency condition must be achieved. The conflict detection frequency condition is controlled by the *AddJCnt* and *AddIPercentOfJ* parameters. The *AddJCnt* is the number of consecutive 10-second processed radar track reports that TrajCP uses to record a conflict notification. *AddIPercentOfJ* is the percentage of the *AddJCnt*

[‡‡]In this study there were approximately 66.9 million flight pairs across the NAS, and approximately 5.1 million flights pairs passed the flight pair gross filter for a reduction of 92.5 percent. The individual results of gross filtering varied among the different ARTCCs.

[§§]For this study, there were 506.7 million track points processed with two trajectories generated per track point. Only approximately 46.5 million trajectory pairs later passed the gross filtering condition, which reduced the number of trajectory pairs probed for conflicts by 91 percent.

parameter track reports that are required to record the conflict notification. An *AddJCnt* of 30 using an *AddIPercentOfJ* of 90 would then require a minimum of 27 of the 30 track instantiated trajectories to declare a conflict. In order to delete the notification of a conflict, the non-conflict detection frequency condition must be achieved subsequent to previously posting a conflict notification. A non-conflict event occurs at a time when either trajectory could not be generated, the trajectories do not pass the spatial gross filter, or the two trajectories do not lose the minimum separation standard. The non-conflict frequency condition is controlled by the *DelJCnt* and *DelIPercentOfJ* parameters. The *DelJCnt* and *DelIPercentOfJ* follow the same logic but is the complement for removal of the conflict notification. Thus, at 30-90, 27 of the 30 track instantiated trajectories would had to have not detected a conflict to remove the conflict notification. Furthermore, the extent to how far into the future TrajCP generates trajectories in order to detect conflicts is set by the look-ahead time, *LH*. The *LH* threshold is another parameter that is user defined. The determination of values for all the user-specified parameters will be presented in a calibration process in Section V.

V. Calibration of the Trajectory Conflict Probe

Experiments are performed by most researchers and scientists in practically all disciplines. An experiment is defined in Ref. 10 as "a test or series of tests in which purposeful changes are made to input variables of a process or system so that we may observe and identify the reasons for changes in the output response." To illustrate this further Fig. 7 presents the general model of a process under study as adapted from Ref. 10. An input stimulus is entered into a process with a set of controllable factors. These are the factors or independent variables in the experiment that are manipulated to study the output or response variables. The uncontrollable factors are not easily manipulated, but through experimental design techniques such as blocking and randomization can be removed from the experiment. The output response variables are the dependent variables of the experiment. They are often determined by application of a metric or measured by a sensor device.

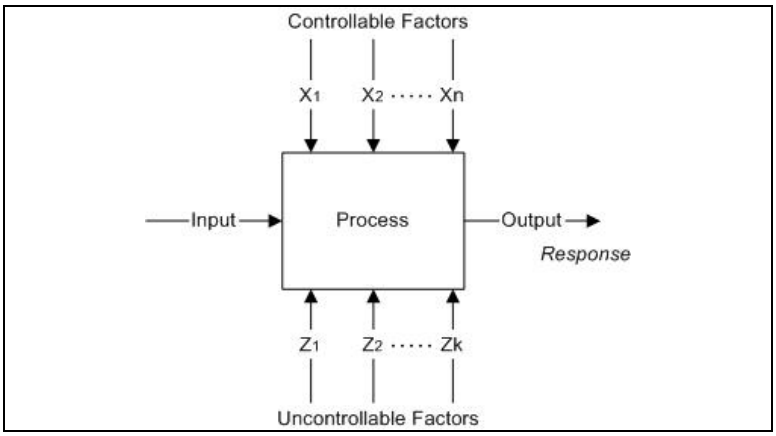

Figure 7: General Model of a Process (adapted from Ref. 10)

There are many purposes of performing an experiment. For this study, the objective was to determine the most favorable parameter settings for the TrajCP model software. There are a potential of six controllable factors to consider, described previously in Section IV, and listed in Table 2. The output response variables include the error rates of missed and false alert events and the mean warning time. The following three sub-sections will present the details of this application of statistical experimental design. Sub-section V.A. will provide an overview of both the controllable and response variables for this experiment. Sub-section V.B. will provide a detailed description of the experiment's design and mathematical model employed. Sub-section V.C. will provide the conclusion of the experiment with a set of recommended parameters for the TrajCP.

A. Experimental Design Factors

As described previously in Section IV, there are six controllable settings or thresholds for the TrajCP software algorithm. Table 2 lists these six factors and the levels or actual values, which the experiment set them to. As review from Section IV, *LH* refers to the modeled look-ahead time that conflict predictions are presented. *MinDetectTime* is the minimum predicted warning time that a conflict will be immediately presented without delay. *AddJCnt* is the number of consecutive 10-second processed radar track reports that TrajCP uses to present a conflict notification.

AddIPercentOfJ is the percentage of the *AddJCnt* parameter track reports that are required to present the conflict notification. Lastly, the *DelJCnt* and *DelIPercentOfJ* follow the same logic but for the removal of the conflict notification.

Table 2: Experiment Factors and Levels

Factor	Levels Implemented***	Units
LH	600, $\boxed{1200}$	Seconds
MinDetectTime	20, $\boxed{60}$	Seconds
AddJCnt	$\boxed{10}$, 30	# of 10s tracks
AddIPercentOfJ	60, $\boxed{90}$	Percent - %
DelJCnt	10, $\boxed{30}$	# of 10s tracks
DelIPercentOfJ	60, $\boxed{90}$	Percent - %

As highlighted earlier, there were three response or dependent variables selected to represent the performance of the TrajCP algorithm examined in this study. The rates of missed and false alerts are the first two and the third is the average warning time. The missed and false alert rates measure the frequency of errors that the TrajCP generates, while the warning time is a quality characteristic of the correct predictions. A conflict probe predicts when two aircraft will violate separation standards some time in the future. A violation of separation standards is typically called a conflict. An event where two aircraft pass near each other but not close enough to violate separation standards is labeled an encounter in this study. As documented in Ref.'s 11-14, the conflict probe is not perfect and does make mistakes. For example, it can miss a conflict (Missed Alert) or it can predict a conflict that never occurs (False or Nuisance Alert). The four possible situations are shown in Table 3.

For a real time system, it is important that an alert be given sufficiently earlier in time of the actual conflict so corrective action can be taken. In other words, an alert must be timely as well as accurate. To ensure timeliness in conflict predictions, a conflict probe is often required to have some lead-time or actual warning time. This Minimum Warning Time (MWT) ranges from 1 to 5 minutes depending on the particular type of conflict probe being evaluated. For this study, 5 minutes was required unless the conflict was determined to be a pop-up event. A pop-up conflict occurs if the probe is not provided with MWT threshold of continuous surveillance data or prediction for either of the associated flights. Detailed descriptions of the different situations that cause this to occur are described in Ref. 14.

Table 3: CP Alert and Conflict Event Combinations (adapted from Ref. 11 and 14)

	CONFLICT OCCURS	**CONFLICT DOES NOT OCCUR**
ALERT	CP predicts conflict and it occurs (VA – valid alert)	CP predicts conflict and it does not occur (FA -- false alert)
NO ALERT	CP does not predict conflict and it occurs (MA -- missed alert)	CP does not predict conflict and it does not occur (NC -- correct no-calls)
Total Number of Alerts	Total Number of Conflicts	Total Number of Non-Conflicts (Encounters that did not have conflicts)

The Missed and False Alert counts are normalized by dividing them by the number of conflicts and alerts they are matched to. The resulting ratios are the rates of Missed and False Alerts. Eq. (1) defines the rate of Missed Alert. It quantifies the likelihood that the conflict probe does not predict the conflict when it occurs.

$$R(MA) = \frac{MA}{C} = \frac{MA}{(MA + VA)} \tag{1}$$

where *MA* is the number of Missed Alerts and *C* is the number of input conflicts from the scenario. *C* is the sum of Missed and Valid Alert events (*C*=*MA* +*VA*) from Table 3.

***Factor level combinations with surrounding box produce the most *desirable* results, see later Section IV.C.

The False Alert rate is defined as the ratio of False Alert events to the total number of alerts presented by the conflict probe. Eq. (2) defines this metric. It quantifies the likelihood that a predicted alert is indeed a false alert.

$$R(FA) = \frac{FA}{A} = \frac{FA}{(FA + VA)} \tag{2}$$

where *FA* is the number of False Alerts and *A* is the number of verified alerts from the probe. *A* is the sum of False and Valid Alert events (*A*=*FA*+*VA*) from Table 3.

The third response variable is the average of the actual conflict warning time. It quantifies the timeliness of the Valid Alert events. The actual warning time is expressed in Eq. (3).

$$WT = ACST - NT \tag{3}$$

where *WT* is the actual conflict warning time, *ACST* is the actual conflict start time, and *NT* is the notification time of the conflict.

The warning time is the lead time that the particular Valid Alert had provided for the conflict event. The average is calculated for the given scenario or traffic sample. The objective of the experiment is to maximize the average warning time for the sample of Valid Alert events, while simultaneously minimizing the rates of the errors.

B. Experimental Design Model

There are many types of experimental designs in the literature. A factorial experiment is a very efficient experiment that evaluates a process under study with many factors.[10,15,16] The experiment is factorial since all the combinations of the levels of these factors are examined. As a result, the main effects of the factors under study are estimated as well as all their interactions. For this study, not only are several factors involved, but we are interested in the range of their effect. This is determined by selecting two levels for each factor, an upper and lower bound. This sub-type of factorial experiment is referred to as a 2^k factorial experiment because there are two to the power *k* combinations of treatment runs to make, where *k* is the number of factors. The selected levels and factors for this experiment are listed in Table 2.

To run the full experiment, there would be 64 (2^6) treatment runs. However, this would include evaluations of 2, 3, 4, 5, and 6-way factor combinations of interactions. A full fractional factorial experiment for the 2^6 factorial will reduce experiment to testing the main effects and only the two-way interactions. It would be difficult to determine what the interactions would even physically mean beyond two-way. However, the key benefit for this study is it reduces the runs by half. Thus, only 32 of the original 64 runs are necessary using a fractional design.

The model assumes a linear combination of an overall effect, treatment effect composed of the main and two-way factor interactions, and an error term for normally distributed random noise. The higher order interactions, beyond two-way interactions, are pooled in this error term. The model is defined in Eq. (4).

$$Y_{ij} = \mu + \tau_i + \varepsilon_{ij} \tag{4}$$

where Y_{ij} is the dependent variable, μ is the overall mean, τ_i is the effect of the ith treatment (effect of the controllable factors), and ε_{ij} is the normally distributed random error term with an assumed 0 mean and equal variances.

The treatment effect in the above model represents the full fractional factorial of the six factors under study. The treatment is therefore composed of the six factors expressed in Eq. (5).

$$\tau_i = \mathrm{A + B + C + D + E + F + AB + AC + AD + AE + AF + BC + BD + BE + BF + CD + CE + CF + DE + DF + EF} \tag{5}$$

where A is the first factor, B is the second factor up to F which is the last factor.

C. Experimental Design Results

To drive the experiment and measure the quantity of Missed, False, and Valid Alerts of the TrajCP software tool, a truth data set of conflicts and input air traffic scenario must be provided to TrajCP. The methods used involve creating a set of pseudo test conflicts by time shifting an actual air traffic recording. This is described in detail in

Ref. 17. The original data source used in this study is an extraction of a ZDC recording from March 2005. It was originally developed for the formal accuracy testing of ERAM's Conflict Probe Tool.[18] It includes a sample of 418 flights with about 230 test conflicts. The actual selection of the six factor levels of TrajCP run time parameters were generated using a commercial statistical software package, called JMP[†††], which are listed in Table 4 below. The factor combinations and results of the three response values are listed in the table accordingly. For example, for the first run in Table 4, the combination of the factors and their levels produced a 3.4% Missed Alert rate, 18% False Alert rate, and 102 second average warning time.

The objective of the experiment is to determine the best levels to set the six factors in order to minimize the Missed and False Alert rates while maximizing the warning time. The model assumes a linear relationship between the variables and a normally distributed error. The JMP statistical software package employed a tool called the Predictor Profiler that implemented the model in Eq. (4) and utilized all three response variables to produce an estimate of the factor levels (i.e. settings for the TrajCP algorithm). The Predictor Profiler calculates estimates of the response variables at any factor level within the defined ranges, but it also provides an estimate of the optimal values. Thus, the optimal factor level combination is listed in Table 2 via borders on the desired levels. It provides guidance on which parameters TrajCP should be set to for its later estimate of the NAS conflict properties.

Table 4: TrajCP Experimental Results

	Factor Variables						Response Variables		
Run Number	LH	MinDetect Time	AddJCnt	AddI PercentOfJ	DelJCnt	DelI PercentOfJ	R(MA)	R(FA)	WT
1	600	20	10	60	10	60	0.0342	0.1812	102.3
2	1200	60	10	60	10	60	0.0340	0.2172	122.2
3	1200	20	10	60	10	90	0.0339	0.1709	121.1
4	600	60	10	60	10	90	0.0340	0.1561	116.5
5	1200	20	10	60	30	60	0.0295	0.1386	133.2
6	600	60	10	60	30	60	0.0297	0.1192	124.0
7	600	20	10	60	30	90	0.0252	0.0973	139.9
8	1200	60	10	60	30	90	0.0252	0.1245	163.4
9	1200	20	10	90	10	60	0.0340	0.1530	95.9
10	600	60	10	90	10	60	0.0470	0.1741	95.8
11	600	20	10	90	10	90	0.0470	0.1255	85.6
12	1200	60	10	90	10	90	0.0340	0.1434	114.5
13	600	20	10	90	30	60	0.0426	0.0927	91.6
14	1200	60	10	90	30	60	0.0297	0.1124	127.0
15	1200	20	10	90	30	90	0.0253	0.0870	131.5
16	600	60	10	90	30	90	0.0338	0.0840	132.6
17	1200	20	30	60	10	60	0.0513	0.1190	65.9
18	600	60	30	60	10	60	0.0601	0.1310	77.9
19	600	20	30	60	10	90	0.0601	0.0913	57.0
20	1200	60	30	60	10	90	0.0513	0.1120	93.7
21	600	20	30	60	30	60	0.0598	0.0678	59.7
22	1200	60	30	60	30	60	0.0468	0.0894	102.3
23	1200	20	30	60	30	90	0.0424	0.0544	97.8
24	600	60	30	60	30	90	0.0551	0.0591	102.2
25	600	20	30	90	10	60	0.0733	0.0851	42.3
26	1200	60	30	90	10	60	0.0558	0.1235	75.5
27	1200	20	30	90	10	90	0.0601	0.0720	57.3
28	600	60	30	90	10	90	0.0647	0.0844	67.3
29	1200	20	30	90	30	60	0.0601	0.0601	60.5
30	600	60	30	90	30	60	0.0647	0.0647	69.5
31	600	20	30	90	30	90	0.0687	0.0313	57.3
32	1200	60	30	90	30	90	0.0472	0.0633	100.9

[†††]JMP is developed by the SAS Institute and used here for all statistical calculations, see www.jmp.com for details.

An estimate of the model adequacy is the R-squared statistic, defined in detail in Ref. 16. It reflects the amount of variation the model accounted for in the observation runs. For this study, the R-squared values for all three response variables were no lower than 0.99, which indicates 99 percent of the observed variable was explained by the model. It is an excellent result. The model estimates that the best rate of Missed Alerts, False Alerts and warning time would be 0.024, 0.097, and 147 seconds, respectively, at the recommended levels provided. These results will be verified in the next Section VI, where TrajCP's performance is validated.

VI. Validation of Trajectory and Conflict Predictions

This section will evaluate the accuracy of the TP's trajectory predictions and TrajCP's conflict predictions. It will compare them to similar (yet much more complex) operational models. URET and ERAM are both en route operational systems that predict trajectories and make conflict predictions. URET is the legacy operational system and ERAM will replace URET and its main input, the HCS, in the near future. By comparing the TP and TrajCP's predictions to these operational systems, one can conclude these research models are representative of the operational systems air traffic control uses in the field. The same formal test traffic scenario from ZDC was used as described in the calibration experiment of Section V. Besides this 2005 ZDC air traffic sample, trajectory accuracy of the TP model is calculated on all twenty ARTCCs using the traffic samples from April 2008. The following sub-Section VI.A will present both trajectory and conflict prediction results compared to the operational systems, and sub-Section VI.B will present trajectory accuracy results NAS wide using the April 2008 data.

A. Comparison to Operational Systems

First the trajectory accuracy is calculated using the same baseline ZDC traffic scenario described in Section V. The mean horizontal and vertical trajectory errors are calculated for all three models, that is URET, ERAM and TrajCP. The horizontal error is the straight line distance between the surveillance radar position and the time-coincident trajectory predicted position. Vertical error is similar being the time-coincident difference between the predicted and actual altitude. These metrics are defined in detail in Ref. 19. Fig. 8 illustrates the results of these error metrics as a function of look-ahead time. It shows that TrajCP's horizontal errors are slightly below URET and ERAM before about five minutes look-ahead time, but get only modestly larger as look-ahead time increases to a maximum of approximately two nautical miles larger at 20 minutes. For the vertical error, TrajCP starts below URET and ERAM performance but reaches a maximum at five minutes (yet only about 100 feet larger), and then steadily descends to match ERAM performance. Therefore, the results confirm that TrajCP's performance is comparable to other NAS automation and in horizontal are only modestly larger at its largest look-ahead time.

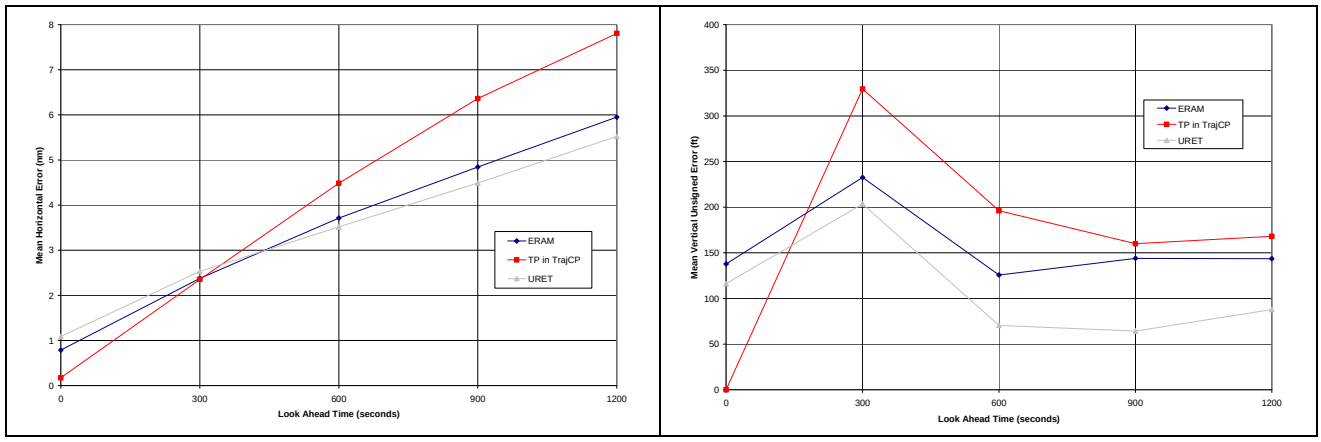

Figure 8: TP Accuracy Results Compared to URET and ERAM

Using the settings determined by the experiment in Section V, the TrajCP was run on the same ZDC traffic scenario and compared to URET and ERAM. The results are tabulated in Table 5. The TrajCP results match what was predicted in Section V. TrajCP's False Alert rate is better than both URET and ERAM. All three systems' Missed Alert rates are comparable. TrajCP's mean warning time is only slightly less than URET and ERAM's. Therefore, it is easy to conclude that TrajCP is very much comparable to URET and ERAM's conflict prediction accuracy.

Table 5: TrajCP Conflict Prediction Results

	URET	ERAM	TrajCP
False Alerts (FA)	88	108	26
Miss Alerts (MA)	8	4	6
Valid Alerts (VA)	234	218	231
Verified Conflicts	242	222	237
Verified Alerts	322	326	257
R(MA)	0.033	0.018	0.025
R(FA)	0.273	0.331	0.101
Avg Warning Time	00:03:46	00:03:42	00:02:25

B. NAS-Wide Trajectory Accuracy

As described in Section III, the data collection for this study includes traffic recordings from all twenty ARTCCs from April 2005 (see Appendix Table 6 for a full listing of the ARTCC NAS codes). Fig. 9 illustrates the variation in trajectory accuracy between the various ARTCCs. Overall, the performance is comparable to the results previously reported in Fig. 8. However, as a function of ARTCC some centers exhibit larger errors while others have significantly less errors. At the 10 minute look-ahead time, the mean horizontal error ranged between 2 and 6 nautical miles for the twenty ARTCCs. ZDV (Denver ARTCC) produced the lowest error, while ZBW (Boston) and ZNY (New York) produced the largest errors at the upper range. Vertically the various ARTCCs performed similarly except ZNY, which peaked with more than double the other ARTCC's vertical errors. Further analysis revealed that ZNY in particular had significantly more transitioning (climbing or descending) aircraft within its airspace, contributing to the larger errors. Therefore, the trajectory accuracy does vary by center in fairly predictable ways, but the overall performance is comparable particularly at the lower look-ahead times.

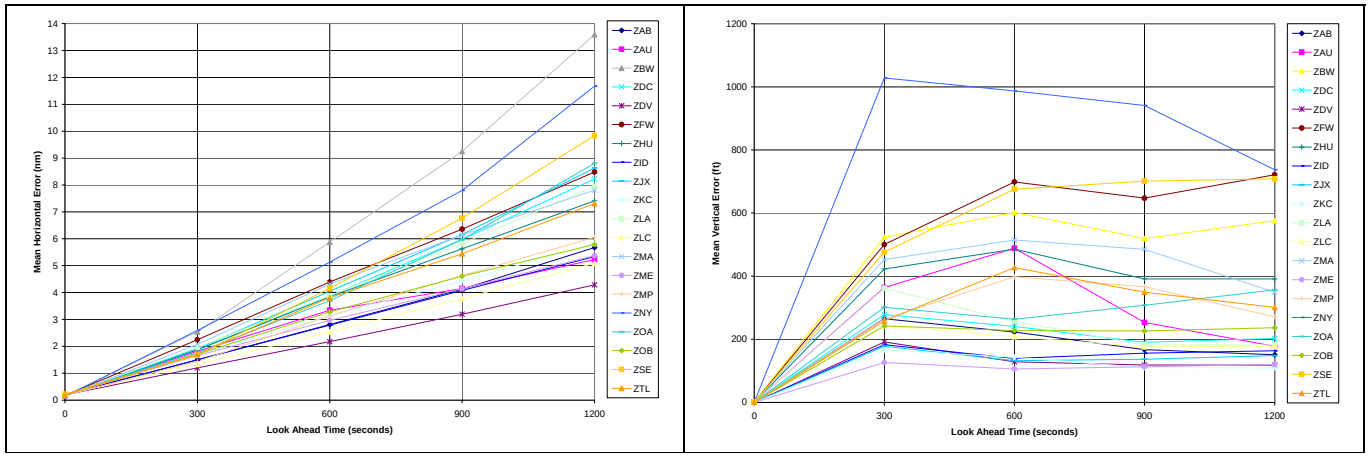

Figure 9: Trajectory Accuracy Results Per ARTCC

VII. Conflict Property Definitions and Results

The properties of the conflict events are the main objective of this research and fall into three basic categories:

1) The *event properties* characterize the conflict events themselves including the state of the aircraft pair involved or the geometry of the event, either spatial or temporal. Examples of these properties include the altitude and latitude-longitude of the aircraft during the conflict event, the minimum separations, the encounter angle, the vertical phase of flight, the conflict duration, and the ground speed differences of the associated aircraft pair.
2) The *interaction properties* characterize the relationships between two or more conflict events or aircraft involved in the conflicts. Examples include the counts of aircraft involved in more than one conflict, the time based interaction metrics that capture the degree temporal overlap between multiple conflicts, and spatial proximity metrics that measure the spatial distances of other conflicts.

3) The *system properties* characterize the conflicts in context of the NAS in which they are found. Examples include the instantaneous conflict counts to active aircraft flying, the instantaneous conflict count per unit time, and the overall counts of conflicts by ARTCC or sector.

This study will present metrics covering all three types of conflict properties. For comparison purposes it will focus on those that replicate conflict properties in Ref. 5 and 6. Starting with the system properties, Fig. 10 illustrates the quantity of flights utilized as a function of ARTCC, while Fig. 11 provides the distribution of the total number of conflicts per ARTCC. The flight count ranged from about 900 flights in Seattle ARTCC (ZSE) to almost 3400 flights in Atlanta (ZTL). The aircraft count and conflict count are correlated. For example, the same sites are at the extremes. ZTL accounted for almost 14 percent of the total conflicts while the next largest was at 10 percent.

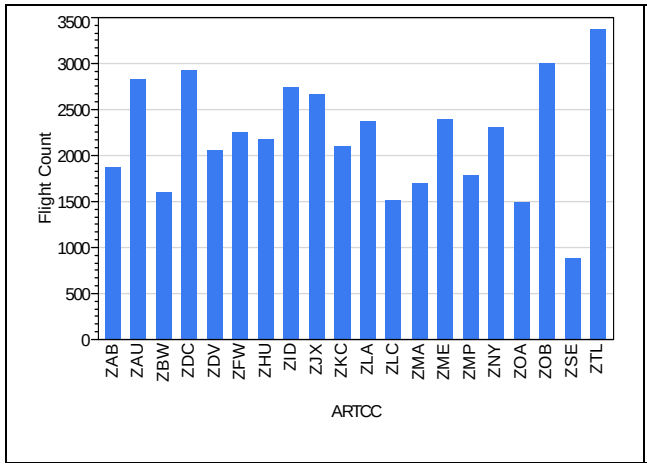

Figure 10: Total Sample Flights by ARTCC

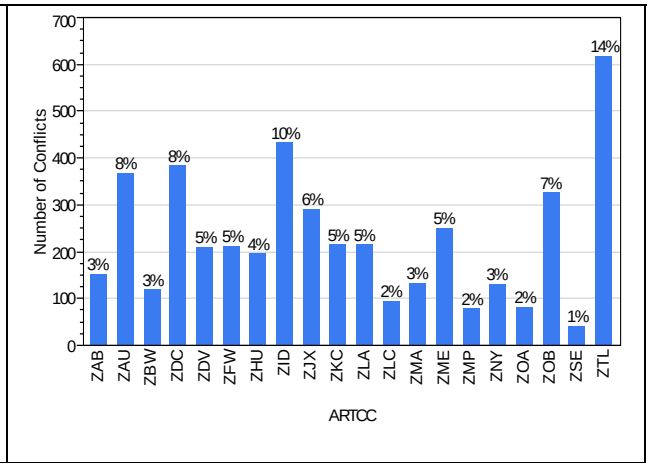

Figure 11: Total Conflicts by ARTCC

Fig. 12 illustrates where the predicted conflicts are distributed horizontally across the United States among the twenty ARTCC facilities. Examination of the figure confirms the relative frequencies from Fig. 11 are consistent. There are heavy concentrations of conflicts along the coastal areas of the United States, peaking in the northeastern part of the country. Areas in the middle section of the country have significantly less predicted conflicts.

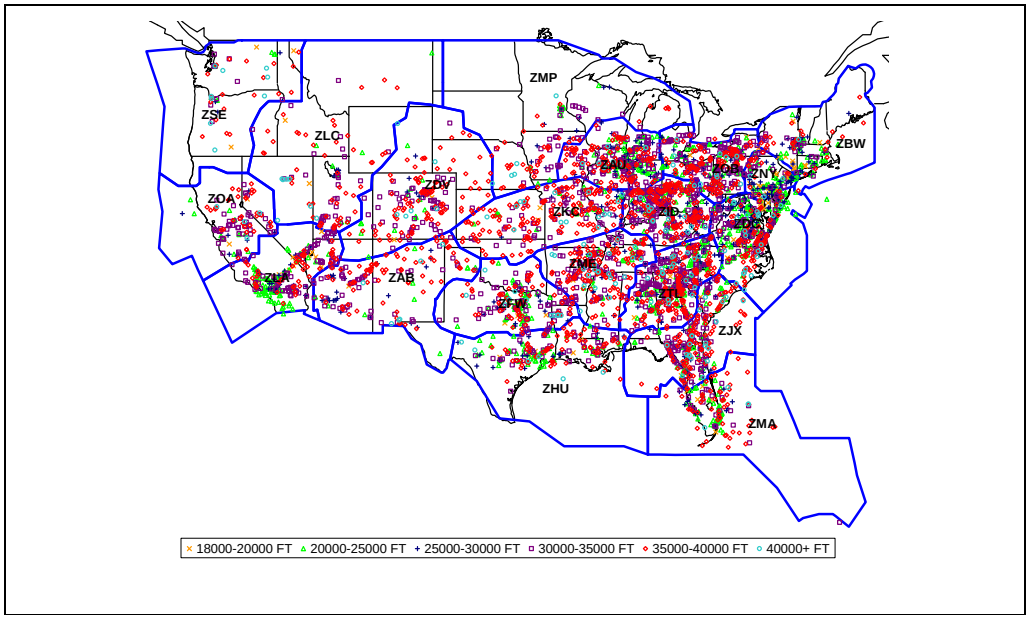

Figure 12: Overlay of Accumulated Conflicts Across the NAS

Section II presented the previous conflict property research by researchers in the United States and Europe. Table 1 in Section II provides an overview of their results. In the Appendix, a similar series of charts is presented using this study's predicted conflicts, partitioned by ARTCC, and linked to Table 1's row numbers.

Continuing the examination of system properties, one of the legacy properties numbered as T-6 presents the number of conflicts as a function of the number of airborne aircraft. This is illustrated in the Fig. 18. It replicates the earlier results of Ref. 5 on a structured routing model of the NAS. In the same manner as the 2001 study, a quadratic least squares fit was used to model the relationship of the two variables. With a quadratic coefficient close to zero, the result confirmed the previous conclusion that the relationship is more linear than quadratic. However, one significant difference from the previous work is the scale of the sample events. The current quantity of conflicts and aircraft are both much higher. The current study ranged in conflicts from 85 to 180 and aircraft from about 4500 to 5500, while the referenced 2001 study ranged in conflicts from 10 to 55 and aircraft 500 to 3000.

Fig. 22 illustrates the instantaneous number of conflict pairs as a function of time for all twenty ARTCCs above FL180. On average, 140 conflicts were active and ranged from 180 at its peak to 28 as the traffic recording ended. The quantity of conflicts more than doubled, as compared to Ref. 5 where the conflicts peaked at about 65 conflicts per unit time. The number of instantaneous aircraft also increased as described above for Fig. 18. While the Ref. 5 study had reported about 2500 to 3000 active aircraft per unit time, this study captured about 4500 to 5500 aircraft explaining the larger conflict counts.

The next category conflict property examined is the event properties starting with one of the most noteworthy in the legacy studies: the vertical phase of flight. The Appendix's Fig. 13 reports on the frequency of vertical phase of flight categories of the conflicts. This was a key discrepancy between the legacy studies from United States and European airspaces. While the Ref. 5 study reported their NAS-wide conflict count had 75 percent of the conflicts as level only events, the current data reported 33 percent were level. This is closer to the Ref. 6's European results of 18 percent. Interestingly, the Northeast ARTCCs of ZNY, ZBW, and ZDC had percentages of 13, 14, and 26 percent, respectively. The Midwest ARTCCs of ZLC, ZDV, and ZKC, were quite different with levels ranging from 45 to 53 percent. This indicates that in regard to vertical phase of flight the NAS is not homogenous. The particular ARTCC and perhaps region of the NAS will indicate the distribution of level versus transitioning conflict events.

The legacy studies both reported their encounter angles of the conflict events but partitioned them by differently. For the current study using the legacy Ref. 5 bins of 0-60, 60-120, and 120-180 degrees, the overall results were 43, 27, and 30 percent, respectively. From Table 1, this is comparable to the legacy United States results. From the legacy European bins of crossing, in-trail, and opposite, the current results are 72, 18, and 10 percent, respectively. These are quite different than the European results. Taking a sub-sample of Northeast ARTCCs, such as ZNY, ZBW, and ZDC as in the previous analysis, the results are closer to the European results at 63, 29, and 8 percent, respectively. Fig. 14 in the Appendix illustrates these percentages as a function of ARTCC.

For the distribution of encounter angle and vertical phase of flight combined, the level-only category and level to non-level bins, are fairly homogenous as a function of ARTCC. This is illustrated in Fig. 15 in the Appendix. However, the non-level to non-level distribution of encounter angle frequencies is more skewed to have more in-trail conflicts (about 10 percent more on average) and less crossing events, while holding the opposite conflict events fairly even. This has operational significance since as aircraft are climbing and descending they are typically on cleared horizontal paths to reduce complexity, making it proportionally more likely to get in-trail conflicts. This result is not universal for all ARTCCs like ZMA (Miami) that seemed to increase its proportion of crossing conflicts when partitioning by vertical phase of flight.

The distribution of conflict frequency as a function of altitude band versus source ARTCC is illustrated in Fig. 16. The average altitude for conflicts is 31,000 feet with a 95 percent confidence interval from 29,800 to 32,100 feet. However, there is a noticeable difference in comparing the overall mean altitude to the Northeast ARTCCs of ZNY, ZBW, and ZDC. Their mean altitude for conflicts is closer to 27,000 feet. The legacy United States study had not reported on altitude and the European study reported a peak around 31,000 feet as well.

In Ref. 6, the European researchers reported the speed quotient as a function of altitude of its conflicts. It is the maximum ground speed divided by the minimum for each predicted conflict. Based on previous work discussed in Ref. 4, the speed quotient is a significant factor in the uncertainty of predicting conflicts and therefore an important conflict property. The European study reported speed quotients ranging from 1.1 to 1.5. For the current NAS study, the average speed quotients per ARTCC ranged from 1.1 to 1.3 as illustrated in Fig. 17.

Conflict duration is the predicted end time of a conflict subtracted by the start time. Appendix's Fig. 19 reported that 74 percent of the overall NAS-wide conflict durations are below one minute, and 14 percent are between one and two minutes. The mean duration is one minute with a standard deviation of about 2 minutes. Fig. 19 presents the durations partitioned by ARTCC. However, the distributions by ARTCC are fairly homogeneous following the same basic pattern of highly skewed to the left for lower durations.

Fig. 20 in the Appendix illustrates the horizontal intrusion distribution. As defined in detail in Ref. 5, the horizontal intrusion value is one minus the ratio formed by dividing the minimum horizontal by standard legal separation (e.g. 5 nautical miles). As a result, the horizontal intrusion is the exact complement to the minimum horizontal separation. For the overall NAS in this study, 41 percent of the conflict events have a horizontal intrusion ratio of less than 0.2. This translates to 41 percent of the conflict events having a minimum separation greater than 4 nautical miles. For the next bin from 0.2 to 0.4 intrusion ratio, 19 percent of the conflicts events had minimum horizontal separation between 3 and 4 nautical miles. In contrast, the vertical intrusion distribution is not illustrated but is highly skewed with about 86 percent in the 0.8 to 1.0 bin. This translates to about zero to 200 feet minimum vertical separation. Fig. 20 indicates that the same pattern of separation exists across the NAS for all ARTCCs and is fairly similar to the legacy results in Ref. 5.

The last category of conflict properties to be examined is the interaction conflict properties. Figure 21 presents the number of aircraft that had encountered one or more conflicts. This replicates the same property presented in Ref. 5. In the 2001 study, 40 percent of the aircraft involved in conflicts had only one event, while the current study reported 79 percent of the aircraft experienced only one conflict. The difference is significant and indicates a change in NAS operations from 2001 to 2008. One key difference that may be responsible is the reduction of vertical separation that began in 2005. These new procedures may have dispersed the current conflicts relative to the 2001 NAS in Ref. 5. Further analysis will be needed to confirm this.

The temporal interaction property provides insight into the time domain relationship of conflicts and the aircraft involved in those conflicts. As defined in Ref. 5 and summarized in Section II, the temporal interaction groups the conflicts per ARTCC into three categories. Strong indicates when multiple conflicts have one or both aircraft in common and the conflict duration (predicted conflict start and end times) overlap in time. None indicates two possibilities. Either both aircraft are unique to the one conflict event, or if this is not the case, the conflict is predicted to occur outside a threshold time (for this study two minutes is used to match Ref. 5) of the second conflict. Weak indicates the later situation but the conflict is predicted to occur within the threshold time without overlapping. For this study as illustrated in Fig. 23, 79 percent of the NAS-wide conflicts were marked “none”, indicating no temporal interaction, while the remaining conflicts were 7 and 14 percent for strong and weak, respectively. This is very similar to the 2001 study in Ref. 5, which reported 84, 6, and 10 percents, for none, strong, and weak respectively. The same pattern did vary per ARTCC ranging from 93 to 66 percent of no interaction category. The second lowest percentage is 74 percent. The much-lower 66 percentage entry belongs to ZTL, where further analysis is required to determine why ZTL is much lower with higher percentages of strong and weak interactions.

VIII. Conclusion

Using the model described in Section IV, the data described in Section III, and calibration and validation in Sections V and VI, the conflicts of the NAS are estimated for a sample period of approximately five hours. Unlike the previous studies, the data is organized by ARTCC for all traffic above FL180. The study provides a comprehensive survey of the conflict properties. These results are described in Section VII in detail and illustrated in the various figures in the Appendix.

The resulting conflict properties provide evidence that the NAS may have increased in traffic and conflict loads, as well as dispersed those conflicts among more aircraft as reported in Fig. 21. A key result is the patterns of diversity of the conflict properties as a function of ARTCC. Not only are the coastal regions involved in a larger quantity of conflicts but typically exhibit different properties such as vertical phase of flight and altitude profile, as illustrated in Fig. 13 and 16.

A striking difference in the Ref. 5 study on the NAS and the European results in Ref. 6 is the vertical phase distribution. The legacy NAS study had reported 75 percent of the conflicts being level events while the European study was much lower at 18 percent. The current study reported a NAS percentage of level-only conflicts at 33 percent. Even more interesting was the result that the Northeast ARTCCs had even lower level-only conflicts ranging from 13 to 26 percent. In regard to vertical transitioning as reported in other studies, for example Ref. 7, these northeastern ARTCCs had similar results to the European airspace.

Therefore, this study developed a set of tools and methodology to predict and then examine the conflict properties of the NAS. It was run using a seven hour traffic sample with almost 40,000 flights, selected from one day in April 2008, incorporating contemporary traffic profiles and aircraft fleet from the NAS. Follow-up studies will capture different sample days, considering seasonal effects on traffic loading and NAS-wide weather effects. Detailed listings of the conflict data and updates on future data collections and results are available by either contacting the authors or referring to the web site at http://acy.tc.faa.gov/cpat/docs/paperCpAiaaGnc2008/.

Appendix

This section will list a series of figures illustrating the conflict properties. The details are in Section VII, but first the NAS ARTCC codes are listed in Table 6 for reference. Next, each figure includes a caption with numerical cross reference to the associated entry from Section II's Table 1. For example, Fig. 13 illustrates the vertical phase of flight distribution. The associated row in Table 1 is 1, so the figure's caption has a label of T-1.

Table 6: NAS ARTCC Code Key

NAS Code : ARTCC					
ZAB	Albuquerque	ZAU	Chicago	ZBW	Boston
ZDC	Washington DC	ZDV	Denver	ZFW	Fort Worth
ZHU	Houston	ZID	Indianapolis	ZJX	Jacksonville
ZKC	Kansas City	ZLA	Los Angeles	ZLC	Salt Lake City
ZMA	Miami	ZME	Memphis	ZMP	Minneapolis
ZNY	New York	ZOA	Oakland	ZOB	Cleveland
ZSE	Seattle	ZTL	Atlantic		

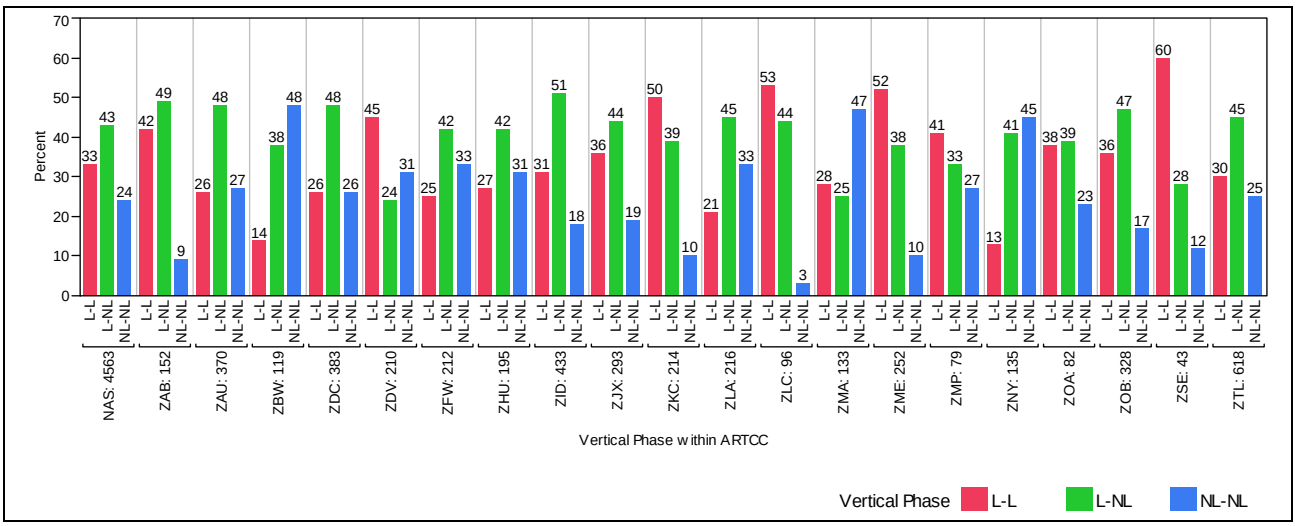

Figure 13: Conflict's Vertical Phase of Flight By ARTCC (T-1)

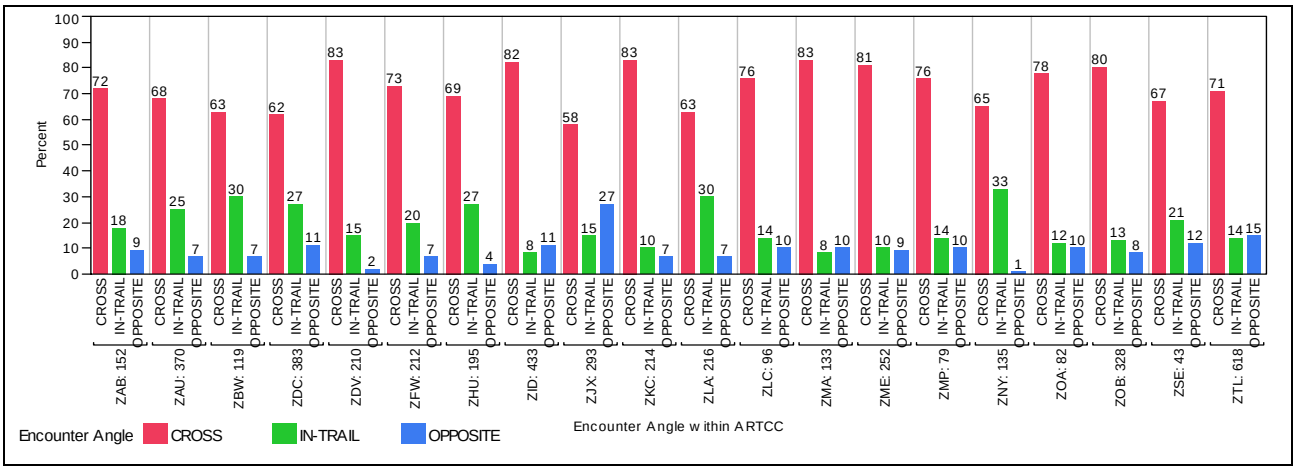

Figure 14: Conflict's Encounter Angle Category per ARTCC (T-2)

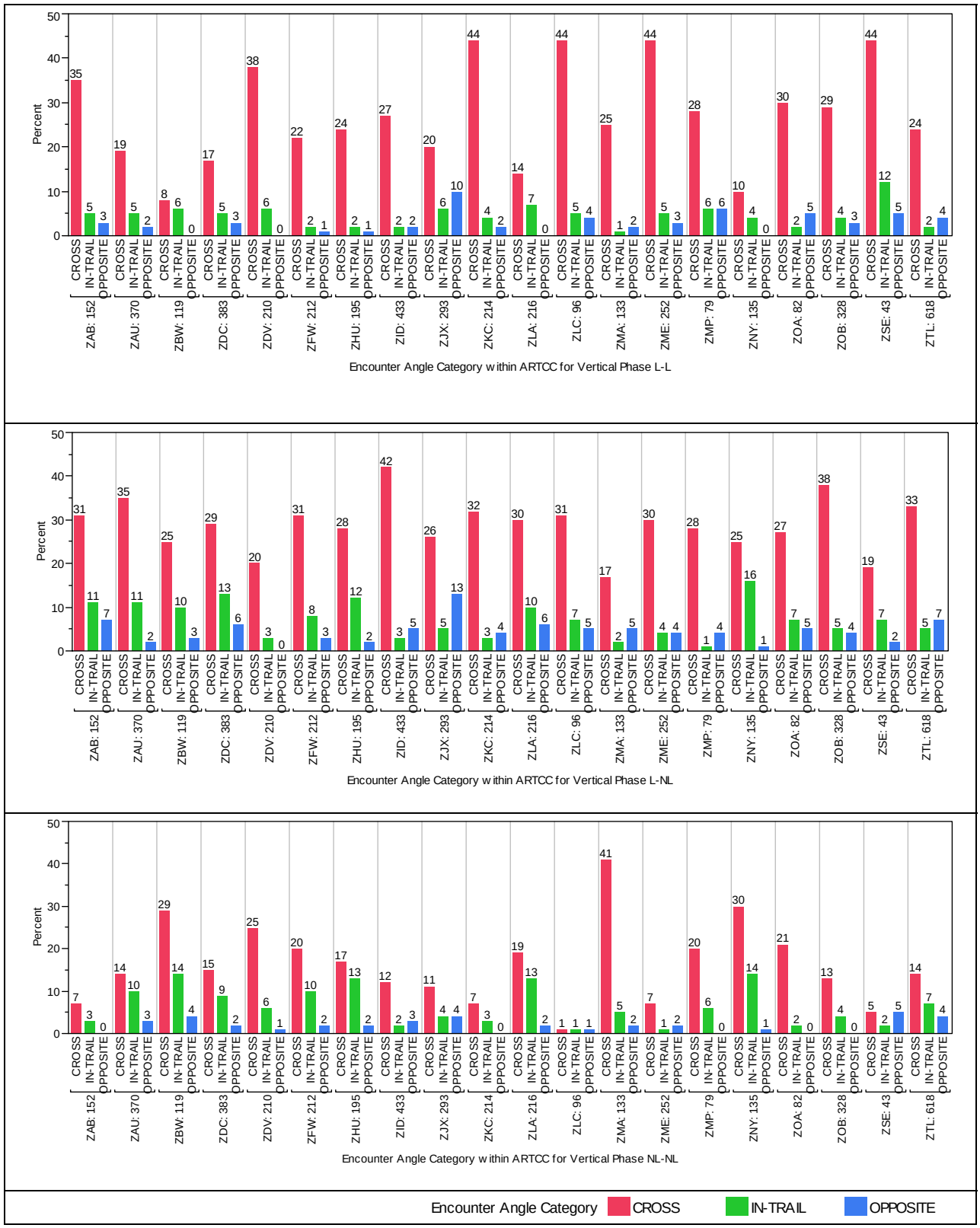

Figure 15: Conflict's Encounter Angle and Vertical Phase of Flight (T-3)

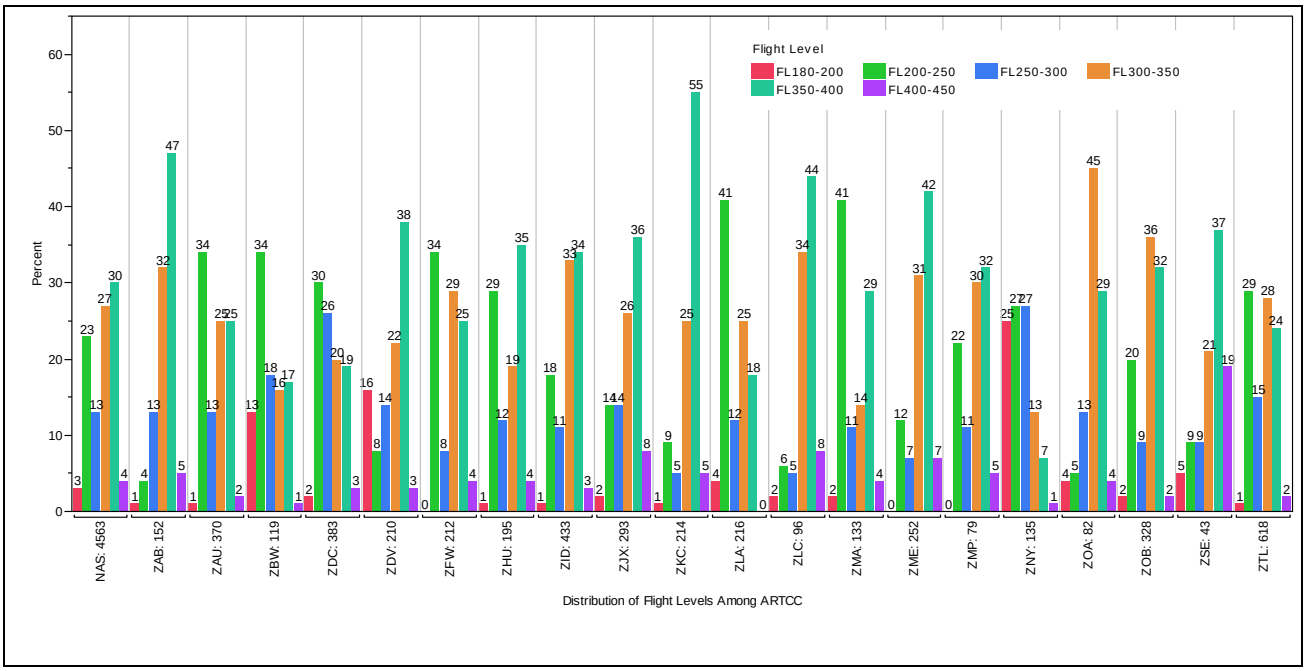

Figure 16: Conflicts by Altitude Band (T-4)

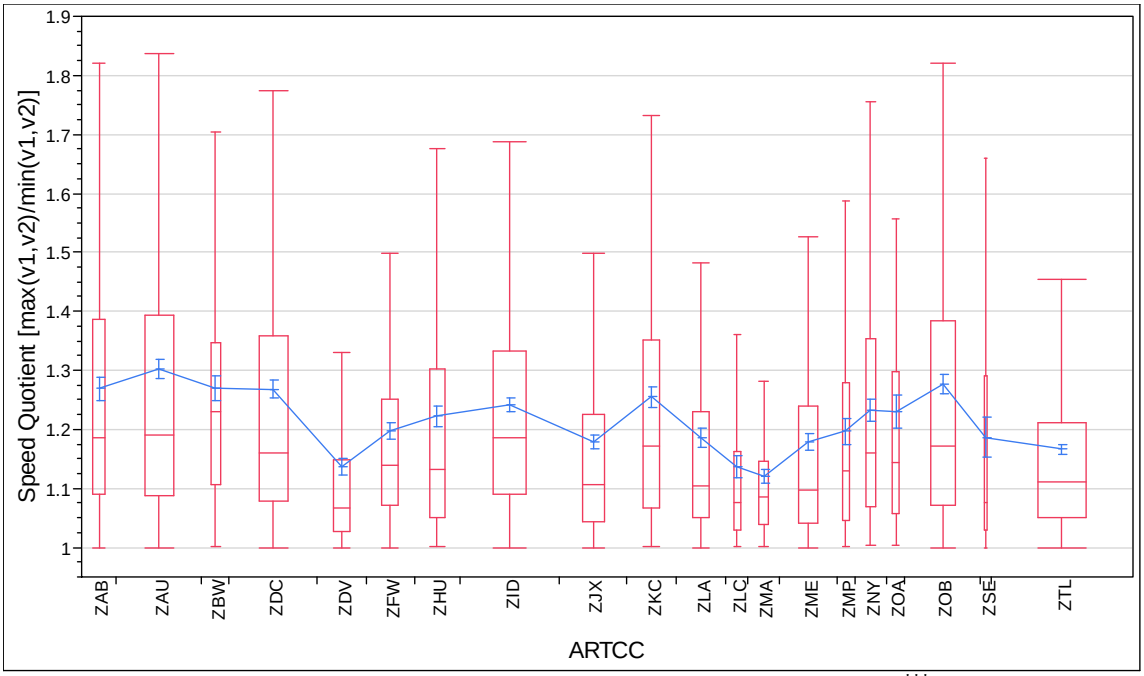

Figure 17: Distribution of Speed Quotient Per ARTCC (T-5)[‡‡‡]

[‡‡‡] The red box plot is formed by the 75th, 50th (median), and 25th percentiles. The box plot's width on the x-axis is proportional to the sample size. The horizontal lines at the top and bottom of the box plot are determined by extending the median by 1.5 times the interquartile range (vertical length of the box plot). The means are connected, centered within the blue brackets, which are formed by plus and minus the standard error.

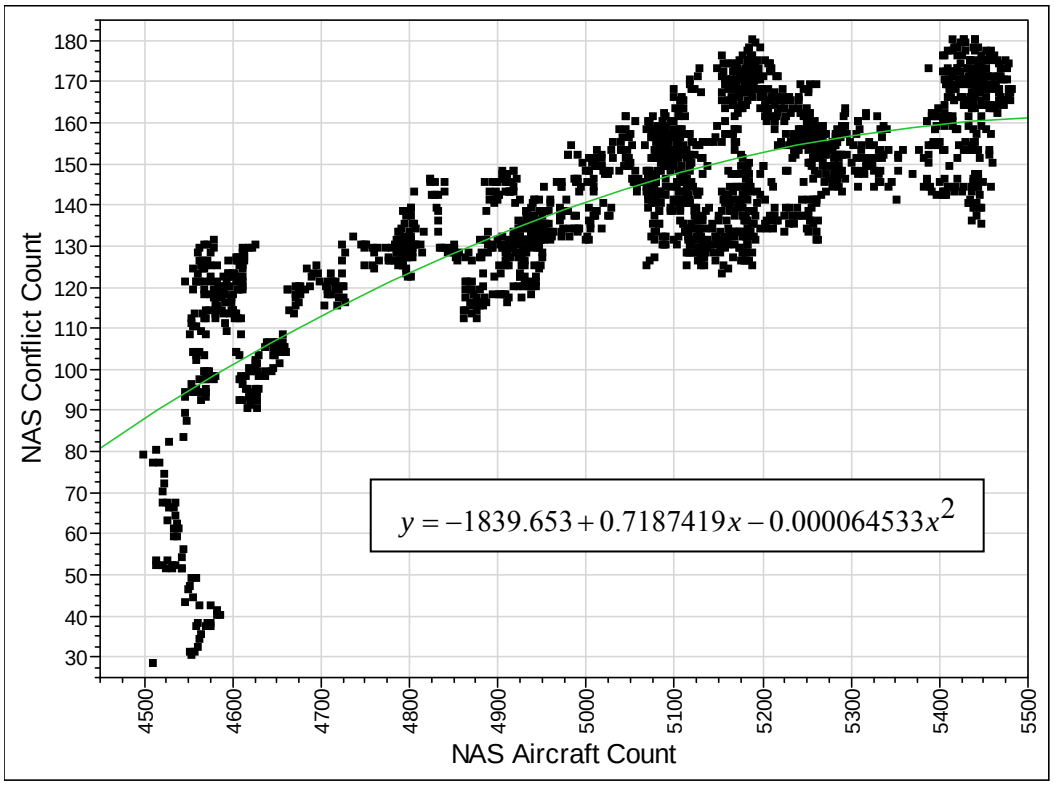

Figure 18: Number of Conflicts by Number of Aircraft Flying (T-6)

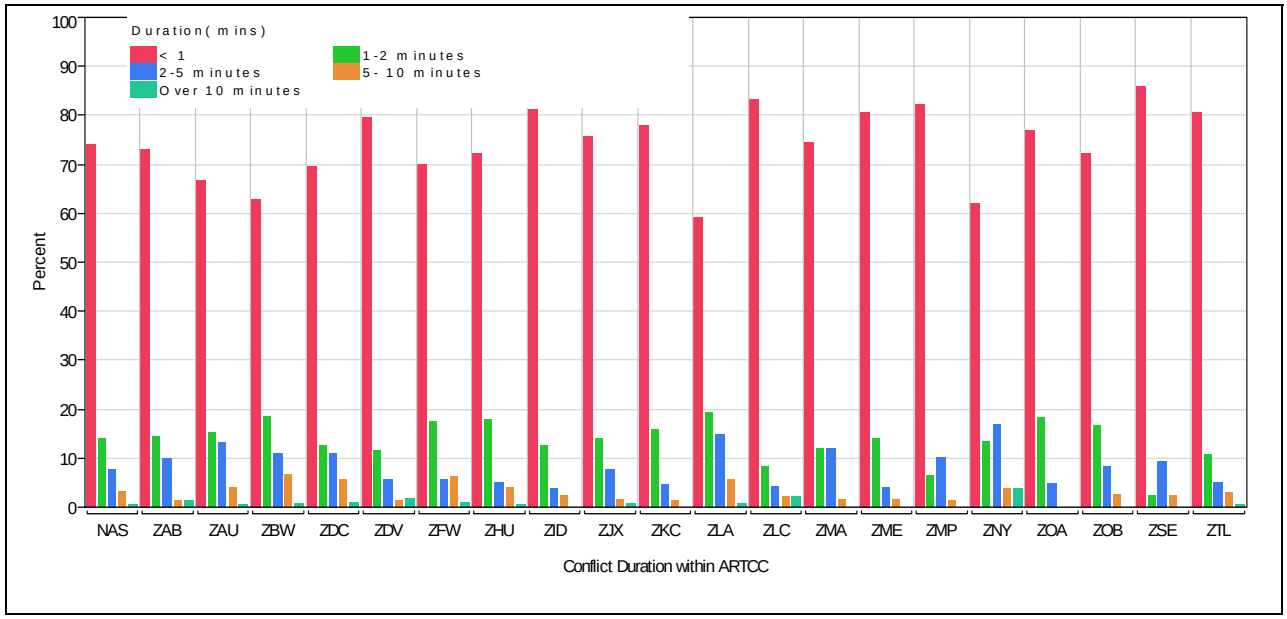

Figure 19: Conflict Duration by ARTCC (T-7)

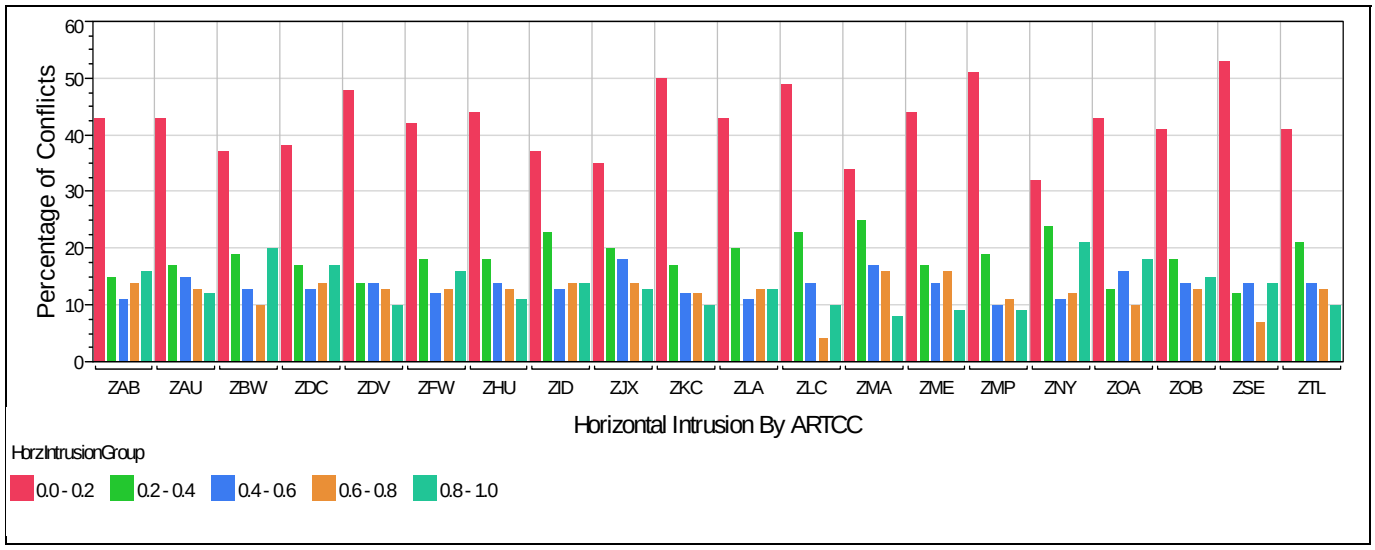

Figure 20: Horizontal Conflict Intrusion Distribution (T-8)

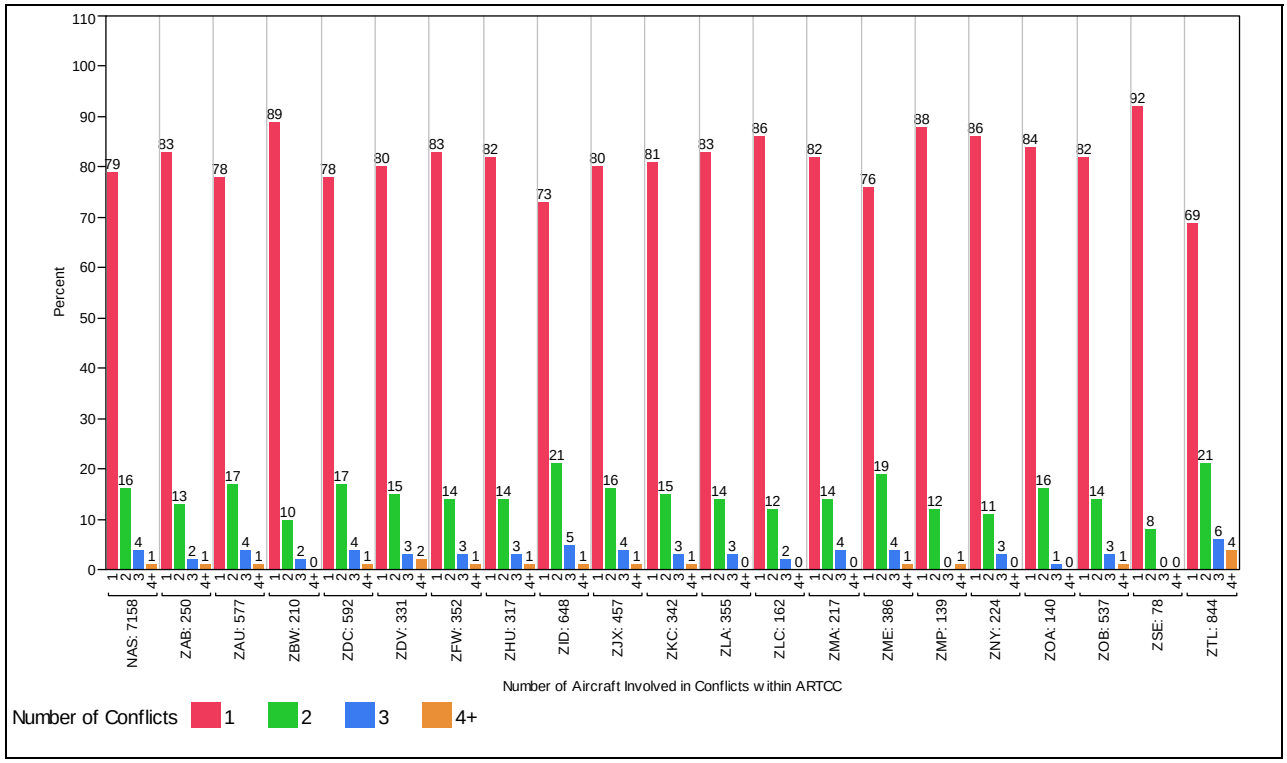

Figure 21: Number of Conflicts Encounter by an Aircraft (T-9)

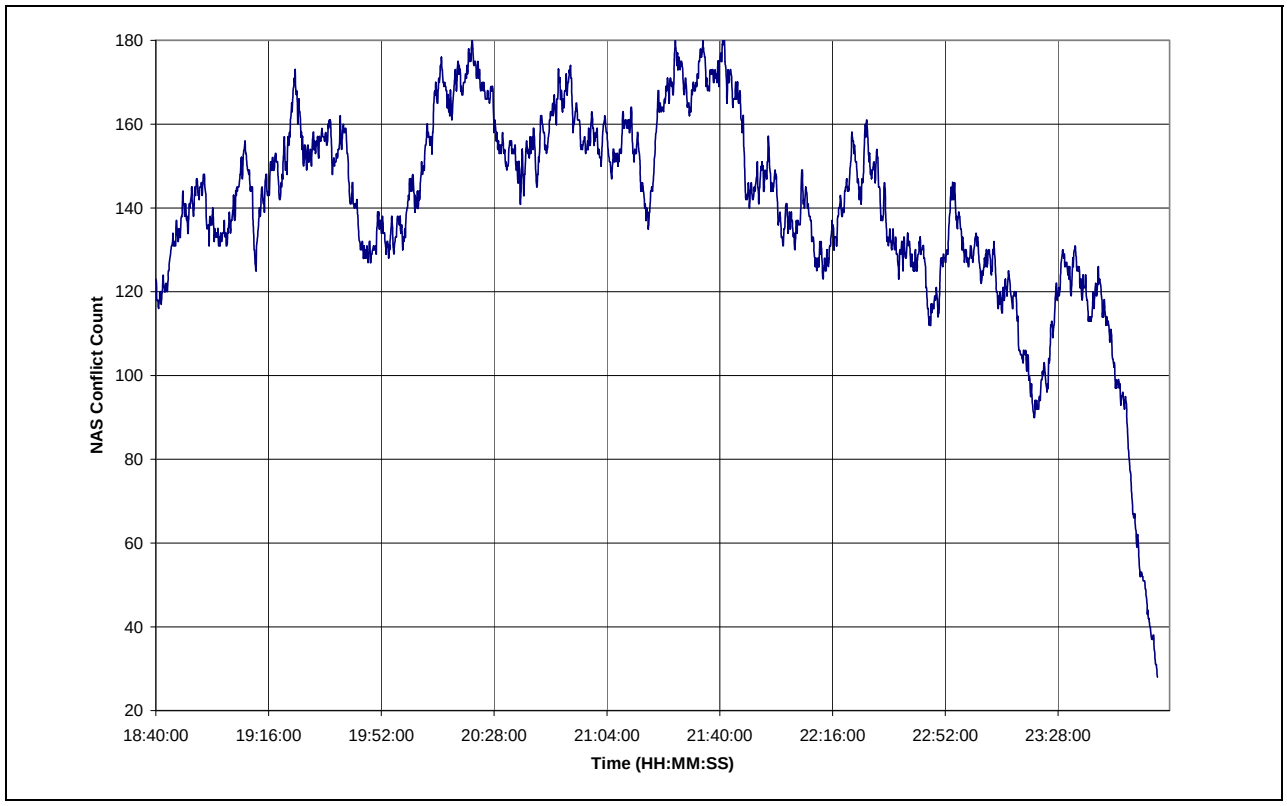

Figure 22: Number of Conflicts per Unit Time (T-10)

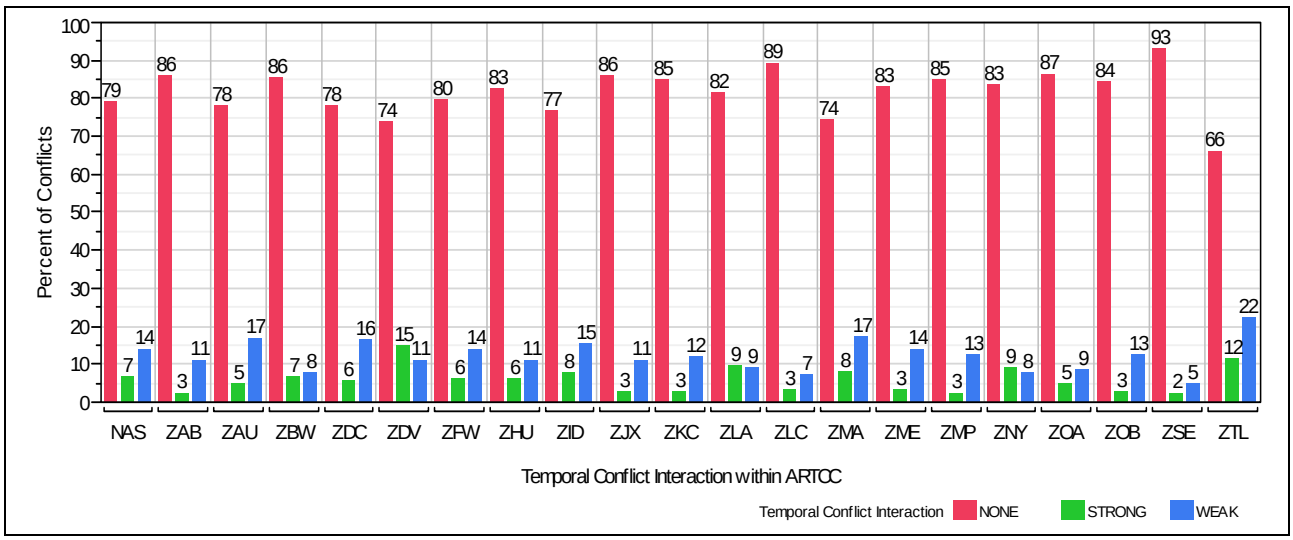

Figure 23: Temporal Conflict Interaction Per ARTCC (T-11)

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