Extended Abstract

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Trajectory Based Operations-
Conflict Resolution Advisories:
A Simulation to Evaluate the Benefits of
Strategic Maneuvering

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Abstract

In today’s aviation system, air traffic controllers manage the separation between aircraft primarily using radar displays to visualize the aircraft positions and their trajectories. They are aided by basic automated decision support tools that predict potential future conflicts. When controllers determine an aircraft must be maneuvered, they advise the aircraft flight crew using two-way radio communications. To maintain today’s high level of safety with the anticipated growth in air traffic, the cost of separation management is expected to increase. Advanced automation is required to aid the air traffic controller and mitigate these costs. One such advanced separation management tool called Conflict Resolution Advisories (CRA) is being developed as a part of the Next Generation Air Transportation System (NextGen) initiative. CRA is a capability designed to aid the controller in formulating more efficient resolution maneuvers while ensuring safe separation of air traffic. CRA will provide a rank-ordered listing of potential conflict resolution maneuvers and is expected to improve operational efficiencies in terms of reduced maneuvering, increased use of fuel efficient maneuvers, more direct routing, and timelier controller actions.

This paper summarizes the results of a fast-time simulation study that investigated the benefits and efficiencies of increased strategic implementations of conflict resolutions using CRA. The objective of the study is to support the cost benefit case for CRA by testing the hypothesis that earlier execution of resolution maneuvers will provide a benefit in regards to maneuvering time and flight fuel consumption. The Airspace Concept Evaluation System (ACES), developed by the National Aeronautics and Space Administration Ames Research Center (NASA/ARC), is a fast-time simulation tool used to simulate ground-to-ground air traffic.

Within ACES, the Advanced Airspace Concept (AAC) package is used to simulate the separation management function by identifying, selecting, and applying conflict resolution maneuvers. Experimental design techniques were used to examine several factors including forecasted traffic demands from three years (2018, 2020, and 2025), three different airspace regions (east, central, and west), and an action time parameter. Action time is a parameter in AAC representing the maximum amount of time prior to loss-of-separation that a resolution maneuver can be implemented. This parameter was set at 5, 7, 9, and 11 minutes to reflect the change from the tactical approach currently used by controllers to the more strategic approach anticipated in the future. Additionally, two uncontrollable factors emerged during the study that significantly affected the responses; these factors are warning time and maneuver type. Four key metrics were used to estimate the benefits associated with the more strategic maneuvering. These were the percent difference of (1) fuel consumption, (2) flight distance, and (3) flight time of a treatment flight compared to its corresponding baseline flight without any maneuvers, and the (4) estimated maneuver delay time associated with each resolution maneuver modeled. Overall, the study predicted that fuel consumption will decrease as action time increases when the warning time is high but increase when the warning time is low. When considering maneuver type, a decrease in fuel consumption is observed for direct-to maneuvers while an increase is observed for vertical maneuvers, both as a function of action time. For both horizontal and speed maneuvers, the benefit is predicted to be marginal. However, the maneuver delay time decreases as a function of action time for all levels of warning time and maneuver types. Overall, more strategic controller actions result in a clear benefit for delay and fuel consumption for large warning times and direct-to maneuvers.
I. Introduction

The Federal Aviation Administration (FAA) created the National Airspace System (NAS), which is composed of a network of air navigation facilities, air traffic control facilities, and airports, along with the technologies and the rules and regulations to operate the system. As the air transportation system in the United States has grown, the NAS has evolved by incorporating new procedures and new technologies. The projected increases in demand could lead to greater stress and perhaps decreased quality of service for NAS users. In response to this the United States Congress created the multi-agency Joint Planning and Development Office (JPDO) in 2003 as a part of the "Vision-100" legislation (Public Law 108-176). The mission of the JPDO is to design and deploy a system meeting the nation's anticipated air transportation needs in 2025. Since its creation, the JPDO has published an integrated plan and documented a concept of operations that establish a vision for the Next Generation Air Transportation System (NextGen). An integral part of this vision is Trajectory Based Operations (TBO), which represents a paradigm shift from clearance-based air traffic control to trajectory-based air traffic control. With TBO, it is envisioned aircraft will fly negotiated trajectories and the air traffic control functions will move to trajectory management.

Air Navigation Service Providers (ANSPs), such as Air Route Traffic Control Centers (ARTCCs) and Terminal Radar Approach Control (TRACON) centers, are components of the NAS. One of the functions provided by the ANSPs is to assist in the separation of aircraft in the air transportation system. Currently separation is managed by air traffic controllers who make strategic and tactical decisions using radar displays to visualize aircraft positions and flight paths. These decisions are then provided to the pilots through voice communications.

NextGen envisions trajectory-based separation management that will provide precise management of the current and future positions of all controlled aircraft in the air transportation system. This will require enhanced Decision Support Tools (DST) that not only predict future conflicts, but also provide conflict resolution that is communicated directly to the aircraft from the ANSP through digital data links. This planned separation management capability will be able to handle the anticipated increase in traffic demand and aircraft diversity with minimal impact to user-desired performance profiles and to the environment, while retaining the existing strict safety standards.

This paper provides a summary of a study identified in the NextGen Project Level Agreement (PLA) titled TBO - Conflict Resolution Advisories - Voice and Datacomm, which identifies the analysis, prototyping, and software development activities required to implement Conflict Resolution Advisories (CRA). The PLA provides the milestones and obligation plan for the FY2010 TBO - Conflict Resolution Advisories - Voice and Datacomm Project. The PLA and the associated benefits plan identify seven potential benefits. The study used a fast-time simulation system to investigate one of these benefits, more efficient maneuvering due to more strategic controller actions.

To investigate this anticipated benefit, the study provided a benefit analysis comparing the current tactical procedures for resolving aircraft-to-aircraft conflicts with the more strategic procedures envisioned for use in the future. The contributors to this study, who worked together under an FAA Interagency Agreement, were the FAA Simulation and Analysis Team (AJP-661) located at the William J. Hughes Technical Center, Atlantic City International Airport, NJ, and the National Aeronautics and Space Administration Ames Research Center (NASA/ARC) located at Moffett Field, CA. Specifically, the FAA was responsible for the study design, making the simulation runs, and performing the data analysis while NASA/ARC provided the fast-time simulation system used in the study as well as software support. The detailed results of the study summarized in this paper are provided in Ref. [10].

II. Study Approach

The overall objective, as already stated in Section I, is to support the cost/benefit analysis of the CRA tool. The following problem statement was formulated to focus resources on how to achieve the overall study objective:

"Through a set of simulation runs using the ACES platform, the experiment shall determine the statistically significant impact that longer action times have on aircraft-to-aircraft conflict resolutions, under different years of traffic forecast and different airspace regions, in terms of the fuel expended, time and distance traveled, and maneuver delays for the simulated flight segments."
Partitioned into the following three sub-sections, Section II details the tools used and the steps taken to address the issues presented in the problem statement. Numerous software applications were used to simulate the air traffic scenarios, calculate the fuel consumption, and statistically analyze the data. In addition to the requisite software, the study design needed to be formulated. This included designating the input and output factors as well as defining key terms to be considered in the experiment. The processes described in this section expanded on the problem statement and laid the framework to quantify the impact that longer action times have on aircraft-to-aircraft conflict resolutions. Later Section III will summarize the analysis techniques employed, Section IV will present the results, Section V will provide concluding remarks, and Section VI will provide a list of recommendations for future studies.

A. Models and Analysis Tools

To evaluate the potential benefits of CRA, the study utilized several software applications and systems ranging from agent-based simulation systems, internally developed applications, and commercially available advanced multi-regression modeling software. The first of these tools, the Airspace Concept Evaluation System (ACES), is a fast-time simulation system provided by NASA/ARC that simulates the NAS. The Advanced Airspace Concept (AAC) package within ACES simulates the separation management function by iteratively resolving conflicts. Collectively, ACES provided the ability to simulate end-to-end air traffic while AAC provided multiple essential functions; namely (1) the ability to evaluate potential resolution maneuvers for each conflict and (2), the logic to resolve conflicts with a maneuver that added the least amount of additional flight time to the maneuvered aircraft. This study also used an application developed by AJP-661 that calculates the amount of fuel consumed by an aircraft during flight based on the European Organisation for the Safety of Air Navigation’s (EUROCONTROL) Base of Aircraft Data (BADA) model version 3.8. This application has been verified previously through comparison with fuel burn metrics from the flight data recorder of an operational FAA test aircraft. Finally, the data analysis was performed using JMP®, which provided modeling capabilities including support of the study’s Design of Experiment (DOE). JMP® is an interactive data visualization and statistical analysis tool available through the SAS Institute* that AJP-661 has used successfully in several other studies.

B. Overall Design of the Study

Figure 1 provides a depiction of the process that the study simulated and analyzed. ACES/AAC was used to simulate the NAS in this process. Its input consisted of an air traffic scenario, controllable factors (year, airspace region, and action time), and uncontrollable factors. Its output consisted of metrics including the fuel consumption, the aircraft delay, the flight distance, and several more as detailed in Ref. [10].

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* The SAS Institute Inc., SAS Campus Drive, Cary, NC 27513.
logic was disabled, providing trajectories and fuel burn calculations for which no deconflicting maneuvers were applied. The specific controllable factors were:

- **Forecast Year** - The air traffic scenarios used in this study were based on the AJG Forecast Schedules, which were derived from 2009 traffic levels. This study used three 24-hour scenarios: the AJG 2018 Forecast Schedule, the AJG 2020 Forecast Schedule, and the AJG 2025 Forecast Schedule.

- **Airspace Region** - This study simulated three pairs of adjacent ARTCCs. Each pair is referred to as a region and was selected to represent a wide range of air traffic operations. The airspace regions were: Oakland (ZOA)/Los Angeles (ZLA), referred to as “West”, Chicago (ZAU)/Indianapolis (ZID), referred to as “Central”, and Boston (ZBW)/New York (ZNY), referred to as “East”.

- **Action Time** – The action time parameter is the amount of time before a conflict at which AAC implements a conflict resolution maneuver. This feature was added to AAC in order to evaluate the benefit of strategic versus tactical conflict resolution. Figure 2 illustrates the action time parameter and its relationship with conflict detection time, resolution start time, and conflict start time. Note that resolution warning time is always limited by detection time.

The four action time values used for this study were 5, 7, 9, and 11 minutes. Regardless of the value of the action time parameter, AAC ensured that the conflict pair would be conflict free for 12 minutes (a parametric value). Figure 3 illustrates how the resolution start time and the resolution maneuver track might vary for resolutions implemented for the same conflict (with the same detection time and conflict start time) in four scenarios applying the various action times.

In Figure 3, the conflict is detected well in advance of the anticipated start time and the resolution warning time is equal to the action time in each scenario. In the 11 minute action time scenario, a resolution maneuver is implemented 11 minutes before the conflict, earlier than in any of the other scenarios. In the 5 minute action time scenario a resolution is implemented just 5 minutes before the conflict. The larger action time represents a more strategic approach to conflict resolution in air traffic control, while the smaller action time represents a more tactical approach.
In some cases a conflict may not be detected early enough to implement a resolution at the specified action time, in other words the detection time is less than the action time. An example of this is presented in Figure 4, where a conflict is detected 8 minutes prior to its start time.

The earliest time a resolution can be implemented is at the time of detection, so in the 11 and 9 minute action time scenarios the resolution is implemented at the time of detection, 8 minutes prior to the conflict start time. This particular case does not affect the performance in the 7 and 5 minute action time scenarios, so resolutions are implemented at the expected time points (7 and 5 minutes before conflict start time, respectively).†

C. Metrics and Parameters

In summary, the factors used in this study are:

- Forecast year, Airspace Region, and Action Time; as defined above.
- Warning Time, which is shown in Figure 2 as Resolution Warning Time.
- Maneuver, which includes direct-to, horizontal (path stretch or parallel offset), speed change, and vertical.

The metrics observed in this study were:

- Percent Fuel Burn Impact‡, which is the net fuel consumption over the portion of the flight path in the CONUS airspace.
- Percent Flight Distance Impact‡, which is the total distance the flight travels in the CONUS airspace.
- Percent Flight Time Impact‡, which is the total time that a flight spends in the CONUS airspace.
- Maneuver Delay Time, which is a measure of the delay time caused by the maneuver.

III. Analysis

The analysis consisted of several parts which are documented comprehensively in Ref. [10]. The two main parts are summarized in this section. First, an examination of selected flight examples illustrated the effects of the input factors on individual aircraft-to-aircraft conflicts. Second, experimental design techniques were used to generalize the impact of these factors to the entire system. As stated in the problem statement in Section II, the goal of the analysis was to estimate the benefits of CRA by measuring the simulated effect of more strategic maneuvering.

A. Conflict Example

The study hypothesized that more strategic resolution maneuvers (i.e., larger action times) would result in more efficient flight paths, a phenomenon that is most evident when ACES/AAC uses direct-to maneuvers to resolve conflicts. Figure 5 depicts a situation where Flight 1 is maneuvered using a direct-to in all four treatment scenarios to avoid losing minimum separation with Flight 2. In this scenario, Flight 1 is an Embraer EJ145 regional jet flying

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† An exception to these modeling behaviors occurs when a flight is within 20 minutes of its arrival fix. If a conflict is detected within this time window it is solved immediately, regardless of the specified action time.

‡ The percent impact metrics were calculated as: [(treatment value – baseline value)/(baseline value)]×100.
between O’Hare International Airport and Charlotte/Douglas International Airport. Flight 2 is a Boeing 737-800 aircraft that is en route from Newark-Liberty International Airport to Los Angeles International Airport.

This crossing conflict, which occurs in the central region with a 2020 traffic level, has an encounter angle of 119.6° and a conflict detection time is 12 minutes and 40 seconds. Since the detection time is larger than any of the action time parameters, Flight 1 is eligible to be maneuvered as soon as it is within the action time threshold of the conflict start time. At the time of the encounter, Flight 1 is climbing to 37,000 ft while Flight 2 is cruising at 36,000 ft; the two flights do not lose separation until Flight 1 has climbed to 36,900 ft.

Figure 5: Horizontal Flight Tracks

Figure 5 illustrates that the action time parameter affects the maneuvers used in the four treatment scenarios. All four maneuvers are direct-to maneuvers that depart the cleared route at different times depending on the action time of the scenario. As the action time increases, Flight 1 is able to start its maneuver earlier, resulting in more efficient maneuvers. Consequently, both the fuel consumption and maneuver delay decrease as a function of increasing action time; this is displayed in Table 1. This example demonstrates how increased action time can reduce fuel consumption and delay when utilizing direct-to maneuvers.

Table 1: Conflict Statistics

<table>
<thead>
<tr>
<th>Action Time (min)</th>
<th>Resolution Type</th>
<th>Number of Options</th>
<th>Maneuver Start Time (min Before First Loss)</th>
<th>Additional Fuel Consumed (lbs)</th>
<th>Maneuver Delay (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Direct-To</td>
<td>18</td>
<td>4.5</td>
<td>-31.56</td>
<td>-64</td>
</tr>
<tr>
<td>7</td>
<td>Direct-To</td>
<td>10</td>
<td>6.5</td>
<td>-41.12</td>
<td>-88</td>
</tr>
<tr>
<td>9</td>
<td>Direct-To</td>
<td>10</td>
<td>8.5</td>
<td>-51.65</td>
<td>-108</td>
</tr>
<tr>
<td>11</td>
<td>Direct-To</td>
<td>10</td>
<td>10.5</td>
<td>-64.87</td>
<td>-122</td>
</tr>
</tbody>
</table>

B. Experimental Models

The experiment performed in the study needed to control the independent factors (controllable factors) and measure the dependent factors (response variables) while minimizing the effect of the uncontrollable factors. The independent factors were the forecast year, the airspace region, and the action time. The response variables included the mean percent fuel burn, percent flight time, percent flight distance, and maneuver delay time for the simulated
conflicts. An uncontrollable factor in this experiment was the warning time of the conflict events. Initially, this factor was not considered, which produced counterintuitive results. Through partitioning the simulated conflicts into bins of warning time (i.e., restricting the randomization), this factor was controlled and its effect was then studied along with the other three factors. Only flights with single maneuvers were selected for the designed experiment analysis which resulted in almost 61,000 flights to examine for the various runs being modeled.

Three experimental models were fit to the simulation results:

- Model 1 (see Eq. 1) was the initial model that established the basic experimental approach. This model represents the full factorial design where all levels and factors are crossed, allowing all the interactions to be examined. This amounts to the four main effects (single variables), six two-way interaction terms (double variables), four three-way interaction terms (triple variables), and one four-way interaction (quadruple variable). The constant or overall mean effect is represented in this model as the “\( \mu \)” term.

- Model 2 (see Eq. 2) modified the initial model to include only the main effects, two-way interactions, and non-linear effects of action time and warning time.

- Model 3 (see Eq. 3) incorporated two major changes. First, it was discovered that the type of resolution maneuver had a significant effect on the responses, so maneuver type was added as a factor. Second, analysis showed that the traffic level’s effect on the four response variables was statistically insignificant, so it was removed from the model.

In these models, the term \( R_{ijkl} \) can refer to any of the four response variables: percent fuel burn impact, percent flight distance impact, percent flight time impact, and maneuver delay time. These response variables are the means for flights with single maneuvers (i.e., one conflict and one maneuver) for each of the various runs and levels. The response variable is an estimate of the expected value for each of these four output functions. In addition, these models assume the random error, \( \varepsilon_{n(ijkl)} \), for each flight \( n \), is independently normally distributed with a zero mean and that the various factors are linearly additive.

Response Models

- **Model 1:**
  \[
  R_{ijkl} = \mu + Y_i + A_j + AT_k + WT_l + (Y_i \times A_j) + (Y_i \times AT_k) + (Y_i \times WT_l) + (A_j \times AT_k) + (A_j \times WT_l) + (A_j \times AT_k \times WT_l) + (Y_i \times A_j \times AT_k) + (Y_i \times A_j \times WT_l) + (Y_i \times AT_k \times WT_l) + (Y_i \times A_j \times AT_k \times WT_l) + \varepsilon_{n(ijkl)} \]
  Eq. 1

- **Model 2:**
  \[
  R_{ijkl} = \mu + Y_i + A_j + AT_k + WT_l + (Y_i \times A_j) + (Y_i \times AT_k) + (Y_i \times WT_l) + (A_j \times WT_l) + (A_j \times AT_k) + (AT_k \times WT_l) + (AT_k \times WT_l) + (WT_l \times WT_l) + \varepsilon_{n(ijkl)} \]
  Eq. 2

- **Model 3:**
  \[
  R_{ijkl} = \mu + M_i + A_j + AT_k + WT_l + (M_i \times A_j) + (M_i \times AT_k) + (M_i \times WT_l) + (A_j \times WT_l) + (A_j \times AT_k) + (AT_k \times WT_l) + (AT_k \times AT_k) + (WT_l \times WT_l) + \varepsilon_{n(ijkl)} \]
  Eq. 3

Where:
- \( Y_i \) = forecast year, \( i = 1, 2, 3 \) (for Eqs. 1 and 2 only)
- \( M_i \) = maneuver, \( i = 1, 2, 3, 4 \) (for Eq. 3 only)
- \( A_j \) = airspace region, \( j = 1, 2, 3 \)
- \( AT_k \) = action time, \( k = 1, 2, 3, 4 \)
- \( WT_l \) = warning time, \( l = 1, 2, 3, 4, \) and 5
- \( \varepsilon_{n(ijkl)} \) = random error, \( n = 1, 2, \ldots \) for all \( i, j, k, l \)
IV. Study Results

As stated earlier, the results presented in this paper are a summary of Ref. [10] with Table 2 providing an overview with cross references to particular sections from the full report. The study concluded that overall, the percent fuel burn impact exhibited a benefit as action time increased when warning time was high but the opposite when it was low. The percent fuel burn impact exhibited a benefit consistently only for direct-to maneuvers and negatively for vertical maneuvers. For both horizontal and speed maneuvers, the benefit was marginal. However, for maneuver delay time the benefit improved as action time increased for all levels of warning time and maneuvers.

Table 2: Summary of Experimental Results and Cross References to Ref. [10]

<table>
<thead>
<tr>
<th>DOE Model &amp; Sections</th>
<th>Flight Example Sections</th>
<th>Maneuver Type</th>
<th>Fuel Burn Trend</th>
<th>Maneuver Delay Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 3 - Section 3.2.2.2.4 &amp; Section 9: Appendix B</td>
<td>3.2.3.6, 3.2.3.1, 3.2.3.2</td>
<td>Direct-to</td>
<td>Decrease as Action Time Increases</td>
<td>Decrease as Action Time Increases</td>
</tr>
<tr>
<td></td>
<td>3.2.3.7, 3.2.3.2</td>
<td>Vertical</td>
<td>Increase as Action Time Increases</td>
<td>Decrease as Action Time Increases</td>
</tr>
<tr>
<td></td>
<td>3.2.3.8</td>
<td>Speed</td>
<td>Marginal Decrease as Action Time Increases</td>
<td>Decrease as Action Time Increases</td>
</tr>
<tr>
<td>Model 2 - Sections 3.2.2.2.2 &amp; 3.2.2.2.3</td>
<td>N/A</td>
<td>All</td>
<td>Decrease as Action Time Increases when Warning Time High, Increase as Action Time Increases when Warning Time Low</td>
<td>Decrease as Action Time Increases for both Low and High Warning Times</td>
</tr>
</tbody>
</table>

To further illustrate the results summarized in Table 2 and show the magnitude of the effects, a set of 3-D surface plots were generated for percent fuel burn impact and maneuver delay responses. Figure 6 presents Model 3’s results for action times and maneuver and Figure 7 presents Model 3’s results for percent fuel burn impact and maneuver delay. Figure 6 shows that the net change of percent fuel burn impact for each maneuver type. This translates to an average increase in percent fuel impact of approximately 0.6% for vertical maneuvers as a function of action time, while direct-to maneuvers produce a savings of approximately 0.3%. The relationship for the maneuver delay time is simpler in that all four maneuver types exhibit a delay reduction as action time increases. This is illustrated in Figure 7 with a negative slope for all four types. As expected, the direct-to and vertical maneuvers have the steepest slope representing the largest effects.

![Figure 6: Surface Plot of %FB Impact by Maneuver Type and Action Time from Model 3](image1)

![Figure 7: Surface Plot of Maneuver Delay Time by Maneuver Type and Action Time from Model 3](image2)
Besides the net effect of the maneuvers as a function of action time, the average overall effect varies per resolution maneuver type. For example, Figure 6 shows that horizontal maneuvers have the highest average, followed by speed maneuvers. However, direct-to maneuvers have the lowest overall average, while vertical maneuvers have the greatest change as a function of action time. For maneuver delay in Figure 7, horizontal and vertical maneuvers have the highest average delays in the 30 to 40 second range, while direct-to maneuvers have a negative maneuver delay time on average ranging from -40 to -60 seconds.

For the overall results of Model 2 not conditioning on maneuver, Figure 8 illustrates the percent fuel burn impact as a function of both action time and warning time. It shows the non-linearity that can be attributed partially to the interactions of the various maneuver types. At low warning times (less than 5 minutes), the percent fuel burn impact increases as a function of action time by about 1.0% as a function of action time. At higher warning times (greater than 11 minutes) it increases non-linearly by about 0.3 % overall.

Figure 9 presents the 3-D surface formed from modeling the maneuver delay time by warning time and action time (note that the action time and warning time axes are reversed in the two figures). This figure shows that at a high warning time (greater than 11 minutes) the maneuver delay decreases rapidly from about 37 to 20 seconds as action time increases. It also shows that the overall decrease at the lower range of warning time (less than 5 minutes) is about 6 seconds.

These surface plots reveal other trends as well. At lower warning times, the average percent fuel burn impact is higher, ranging from 1% to 2%, since more drastic maneuvers are required to ensure separation distances. At higher warning times, the average fuel burn ranges from about 0.5% to 0.1%. For the maneuver delay, the same surface levels behave quite differently. At the lower warning time, the average delay time ranges from -10 to -20 seconds while at the higher warning time, the average is between 20 to 40 seconds. This indicates the multi-dimensional nature of the solution space under study and the need to consider all the variables involved to properly estimate their net effects.
V. Conclusions

CRA is envisioned as an advanced decision support tool for air traffic control deployed within the NextGen TBO initiative. It predicts, resolves, and ranks future conflicts between aircraft, supporting more strategic separation management of aircraft. Contrasted with the more tactical methods used in today’s operations, performing air traffic control functions more strategically allows potential conflicts between aircraft to be solved sooner. It is hypothesized that this additional lead time will produce more efficient resolution maneuvers.

The objective of this study was to investigate the benefits of resolving conflicts earlier. The assumption that CRA will provide the means to perform more strategic controller actions will be validated in separate studies. Both Ref. [10] and this paper document these potential benefits by applying four key metrics to the modeled results from the advanced ACES/AAC fast-time simulation platform. The first three metrics or response variables include the percentage difference of fuel, flight distance, and flight time between a treatment flight and a baseline flight without any maneuvers. The fourth metric is the estimated maneuver delay time associated with each resolution maneuver modeled.

This initial study established a sound methodology utilizing several powerful tools and platforms from agent based simulation, aircraft energy balance equations to estimate fuel, both internally developed and commercial off-the-shelf statistical and graphical platforms, and advanced multi-regression modeling to synthesize the results and estimate the net effects. In conclusion, the study estimated that the fuel consumption was reduced about 0.3% when resolutions were solved more strategically (i.e., when action time was larger) but only when the warning time of the conflict was sufficiently large; otherwise it is considered a tactical situation and using more strategic actions does not apply. The resolution geometry or maneuver type was another important consideration and based on the ACES/AAC model; direct-to maneuvers provide the only consistent benefit as a function of action time.

VI. Recommendations for Future Studies

This is one of a series of studies to estimate a number of potential benefits of CRA. Being the first in the series, a number of lessons learned have been documented for later studies to build upon. Some of these include:

- The methodology did require extensive filtering to remove flights either exhibiting modeling issues or were out of scope (e.g. international flights, VFR flights, low altitude terminal area flights). A number of the modeling issues are being investigated and improved upon. Future studies should examine the list of issues to ensure they have been all addressed.
- The ACES/AAC simulation model generated a number of conflict resolution maneuvers per detected conflict pair and selected the maneuver that produced the minimum maneuver delay. The results indicate that an alternative selection criterion should be the estimated fuel burn. Future development ACES/AAC simulation model to incorporate such a criterion is being pursued.
- Vertical maneuvers exhibited a negative benefit (cost) in terms of fuel burn impact as a function of increasing action time. This was not the expected benefit. This result was explained in detail in Ref. [10] through several example flights and resolution maneuvers, as well as discussed with ACES/AAC developers at NASA. However, a detailed examination of this phenomenon in ACES/AAC vertical maneuver modeling is recommended prior to future studies using the tool.

§A subset of recommendations is presented in this paper and a complete list is provided in Section 5 of Ref. [10].
References


