# Fast-Time Simulation of Conflict Resolution Advisories to Evaluate Benefits from Strategic Maneuvering

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**An 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 air traffic controllers by providing a rank-ordered listing of potential conflict resolution maneuvers that ensure safe separation of air traffic. It is expected to result in more strategic resolution maneuvers, thereby improving operational efficiencies. A fast-time simulation study by the Concept Analysis Branch investigated this expected benefit using the Airspace Concept Evaluation System (ACES), developed by the National Aeronautics and Space Administration Ames Research Center (NASA/ARC), and within ACES, the Advanced Airspace Concept (AAC) package. Experimental design techniques were applied to study several factors including three future years of forecasted traffic demand, three different airspace regions, and an action time parameter which indicates how far in advance of a predicted conflict the resolution could be issued. Large values of the action time parameter represent the change from the tactical approach currently used to a more strategic approach anticipated in the future. The results of the experimental study are discussed in depth and compared to the results from an independent study by NASA/ARC.**

## I. Introduction

THIS paper provides a summary of a study first identified in the 2010 NextGen Project Level Agreement (PLA) titled *TBO - Conflict Resolution Advisories - Voice and Datacomm*[1], 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 CRA project. The PLA and the associated benefits plan[2] identify seven potential benefits. The study uses 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 current tactical procedures for resolving aircraft-to-aircraft conflicts are compared to the more strategic procedures envisioned for use in the future. The contributors to this study, who worked together under an FAA Interagency Agreement[3], are the FAA Concept Analysis Branch (ANG-C41) 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

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NASA/ARC's main role was to provide the fast-time simulation system used in the study as well as software support. A comprehensive technical documentation of the fast-time simulation study is presented in Ref. [4].

## 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 a single set of experiments and thereby 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 system of flights."*

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 includes 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. Section III summarizes the analysis techniques employed and provides an example from analysis results of how larger action times affect the resolution applied. Section IV summarizes results from the set of experiments completed by the authors and a brief overview of a follow-up experiment completed by NASA. Finally, Section V presents concluding remarks for the overall study.

### 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 National Airspace System (NAS). The Advanced Airspace Concept (AAC) package within ACES simulates the separation management function by iteratively resolving conflicts[5,6]. 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 ANG-C41 that calculates the amount of fuel consumed by an aircraft during flight based on the European Organization for the Safety of Air Navigation's (EUROCONTROL) Base of Aircraft Data (BADA) model version 3.8[7]. This application has been verified previously through comparison with fuel burn metrics from the flight data recorder of an operational FAA test aircraft[8]. 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 ANG-C41 has used successfully in several other studies[9,10].

### 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. [4].

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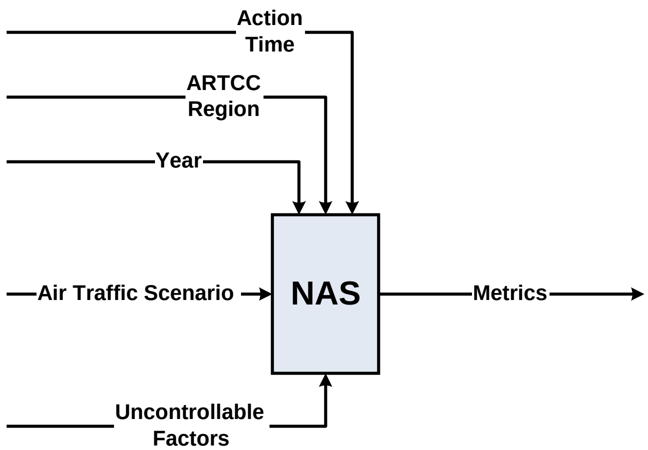


**Figure 1: Model of the NAS Process Being Studied**

There were three forecast years, three airspace regions, and four action times resulting in a total of 36 simulation test cases (3 forecast years × 3 airspace regions × 4 action times). The 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) and Los Angeles (ZLA), referred to as "West", Chicago (ZAU) and Indianapolis (ZID), referred to as "Central", and Boston (ZBW) and 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.

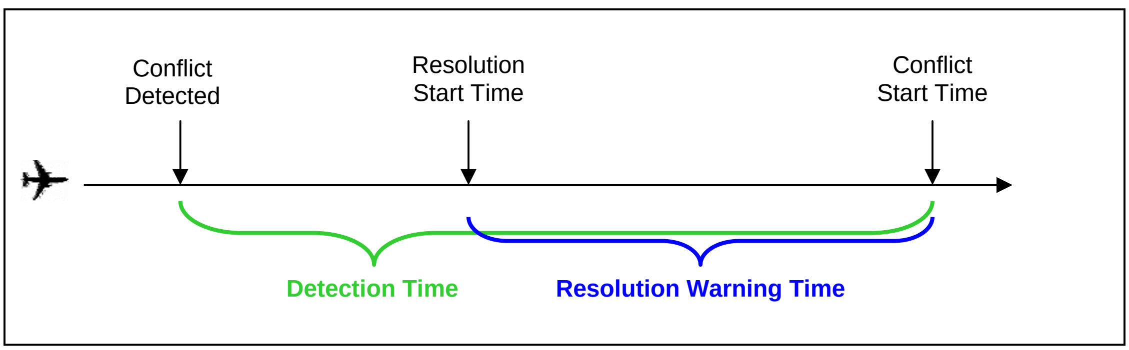


**Figure 2: Conflict Detection and Resolution Timeline**

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.

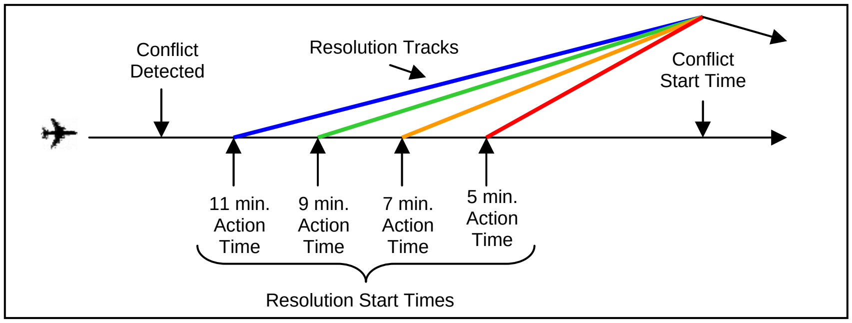


**Figure 3: Action Time Definition- Large Detection Time**

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.

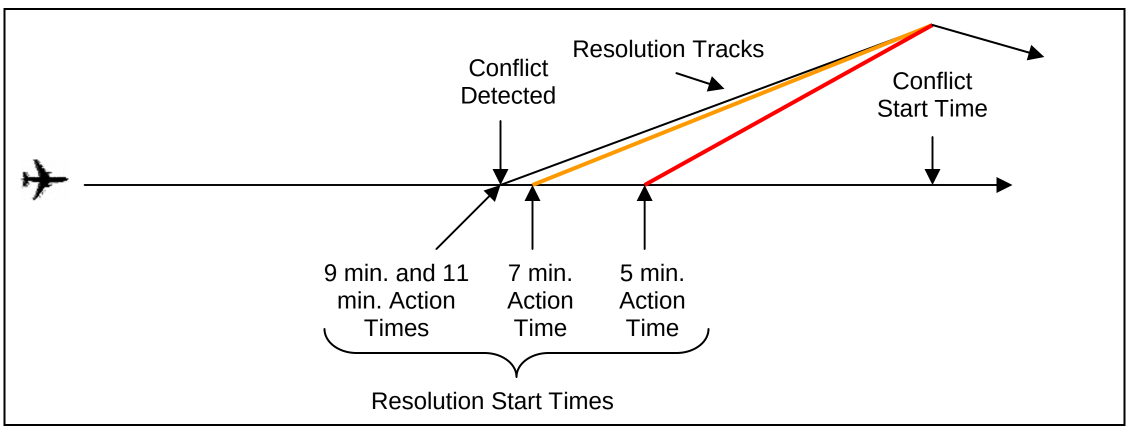


**Figure 4: Action Time Definition- 8 Minute Detection Time**

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. The maneuver types chosen also affect the outcome; these includes direct-to, horizontal (path stretch or parallel offset), speed change, and vertical.

The metrics observed in this study were:

- **Fuel Burn**, the net fuel consumption over the portion of the flight path in the contiguous United States (CONUS) airspace
- **Flight Distance**, the total distance the flight travels in the CONUS airspace
- **Flight Time**, the total time that a flight spends in the CONUS airspace
- **Maneuver Delay Time,** a measure of the delay time caused by the maneuver

## III. Analysis

The analysis consisted of several parts which are documented comprehensively in Ref. [4]. 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 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. In Figure 5 the "Baseline Tracks" show what the route of the flights would be if no conflict resolution was applied.

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.

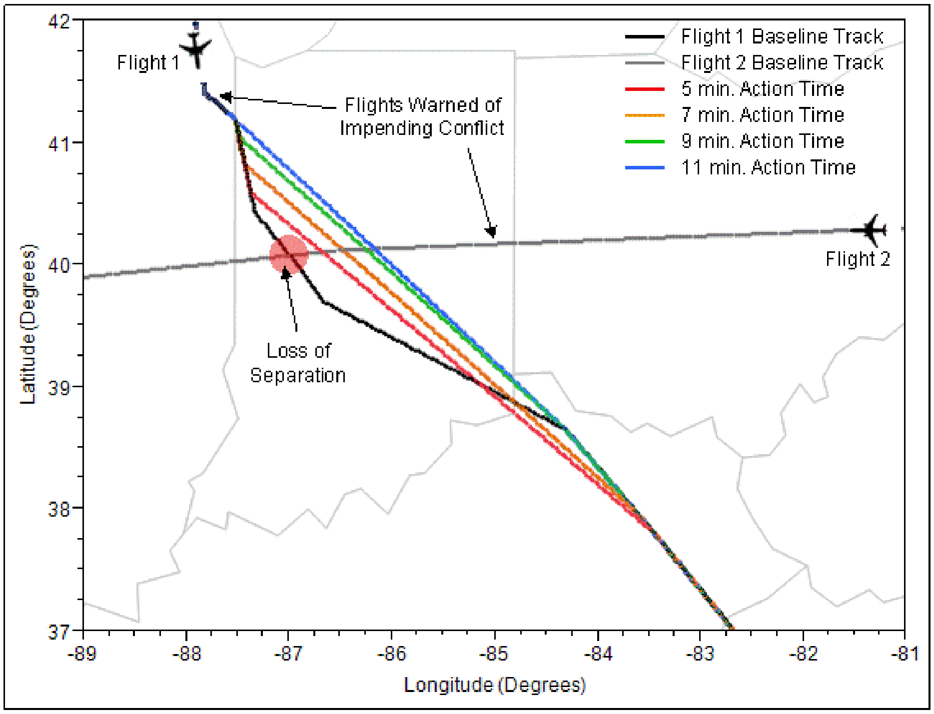


**Figure 5: Horizontal Flight Tracks**

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. The fuel consumption is compared to the fuel consumed in a baseline scenario with no conflict resolution. This example demonstrates how increased action time can reduce fuel consumption and delay when utilizing direct-to maneuvers.

**Table 1: Conflict Statistics**

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

### 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 uncontrollable factors. The independent factors were the forecast year, the airspace region, and the action time. The response variables included the overall system fuel burn, flight time, 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 of Model 2 showed that the traffic level's effect on the four response variables was statistically insignificant, so it was removed from this 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:**

$$R_{ijkl} = \mu + Y_i + A_j + AT_k + WT_l + (Y_i \times A_j) + (Y_i \times AT_k) + (Y_i \times WT_l) + (A_j \times WT_l) + (A_j \times AT_k) + (AT_k \times WT_l) + (Y_i \times A_j \times AT_k) + (Y_i \times A_j \times WT_l) + (Y_i \times AT_k \times WT_l) + (A_j \times AT_k \times WT_l) + (Y_i \times A_j \times AT_k \times WT_l) + \varepsilon_{n(ijkl)} \quad \text{Eq. 1}$$

**Model 2:**

$$R_{ijkl} = \mu + Y_i + A_j + AT_k + WT_l + (Y_i \times A_j) + (Y_i \times AT_k) + (Y_i \times WT_l) + (A_j \times WT_l) + (A_j \times AT_k) + (AT_k \times WT_l) + (AT_k \times AT_k) + (WT_l \times WT_l) + \varepsilon_{n(ijkl)} \quad \text{Eq. 2}$$

**Model 3:**

$$R_{ijkl} = \mu + M_i + A_j + AT_k + WT_l + (M_i \times A_j) + (M_i \times AT_k) + (M_i \times WT_l) + (A_j \times WT_l) + (A_j \times AT_k) + (AT_k \times WT_l) + (AT_k \times AT_k) + (WT_l \times WT_l) + \varepsilon_{n(ijkl)} \quad \text{Eq. 3}$$

**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, … for all $i, j, k, l$**

## IV. Results

The initial results from the fast-time simulation study are summarized in section IV-A. NASA/ARC conducted a follow-up study and a summary of the relevant findings from that effort is presented in IV-B.

### A. Initial Study Results

The results in this section are a summary of those presented in Ref. [4]. Table 2 below summarizes these results and cross references particular sections in that document. 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. [4]**

| DOE Model & Sections | Flight Example Sections | Maneuver Type | Fuel Burn Trend | Maneuver Delay Trend |
|---|---|---|---|---|
| Model 3 - Section 3.2.2.2.4 & Section 9: Appendix B | 3.2.3.1, 3.2.3.4, 3.2.3.5 | Horizontal | Marginal Decrease as Action Time Increases | Decrease as Action Time Increases |
| | 3.2.3.6, 3.2.3.1, 3.2.3.2 | Direct-to | Decrease as Action Time Increases | Decrease as Action Time Increases |
| | 3.2.3.6, 3.2.3.7, 3.2.3.2 | Vertical | Increase as Action Time Increases | Decrease as Action Time Increases |
| | 3.2.3.8 | Speed | Marginal Decrease as Action Time Increases | Decrease as Action Time Increases |
| Model 2 - Sections 3.2.2.2.2 & 3.2.2.2.3 | N/A | All | Decrease as Action Time Increases when Warning Time High,<br>Increase as Action Time Increases when Warning Time Low | Decrease as Action Time Increases for both Low and High Warning Times |

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 the results of the third model for percent fuel burn impact by action times and maneuver type and Figure 7 presents the results of the third model for maneuver delay. Figure 6 shows 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.

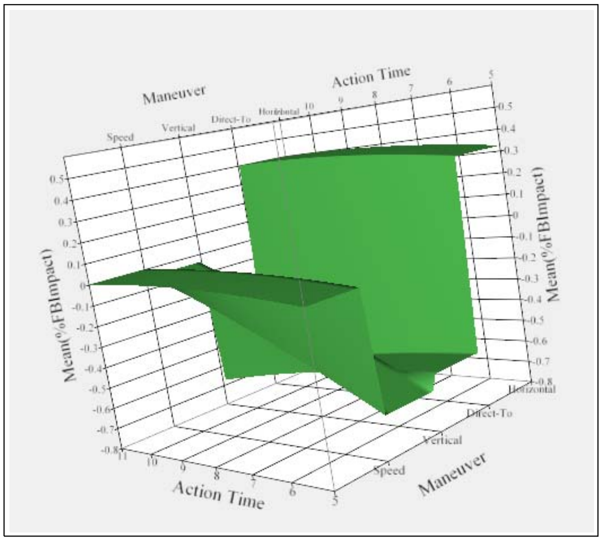


Figure 6: Surface Plot of %FB Impact by Maneuver Type and Action Time from Model 3

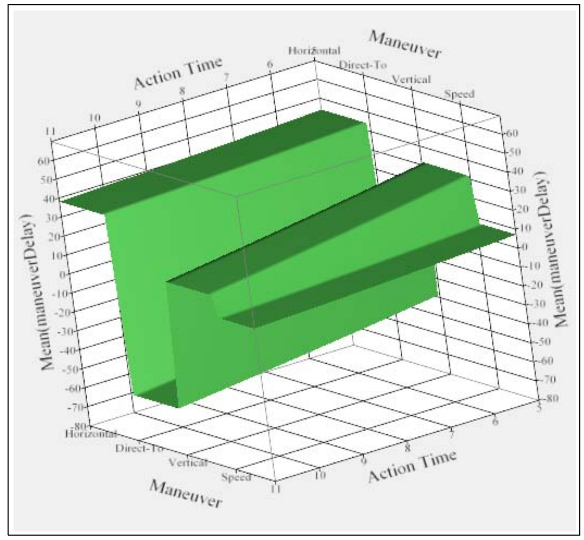


Figure 7: Surface Plot of Maneuver Delay Time by Maneuver Type and Action Time from Model 3

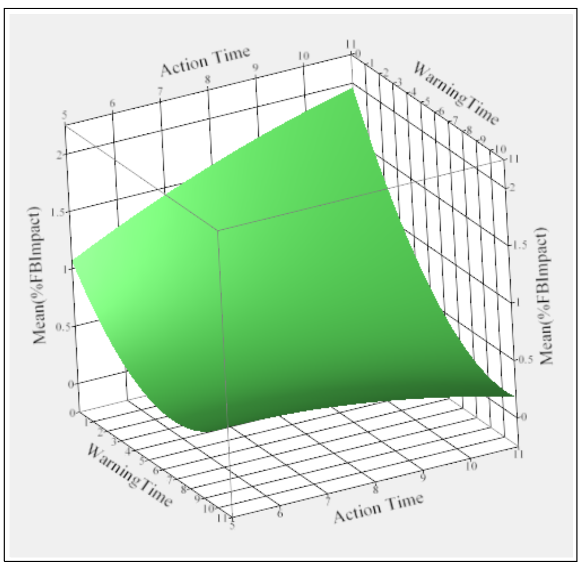


Figure 8: Surface Plot of %FB Impact by Action Time and Warning Time from Model 2

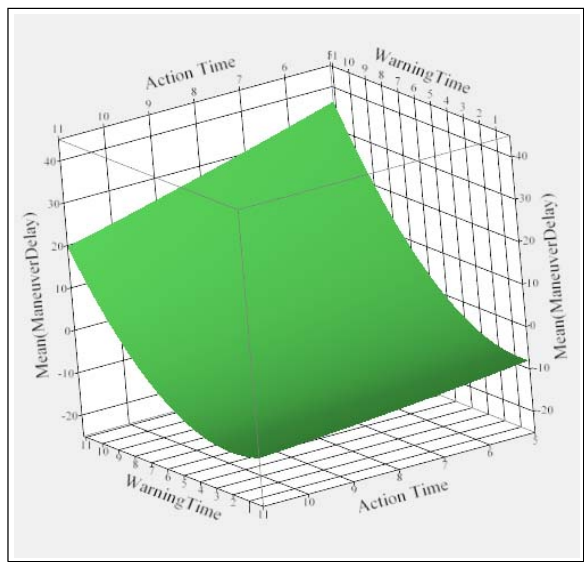


Figure 9: Surface Plot of Maneuver Delay Time by Action Time and Warning Time from Model 2

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 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.

### B. Follow Up Analysis

NASA/ARC, the developer of the ACES/AAC simulation software, performed a follow-up study[11] on the effect of action time on maneuver efficiency with some revisions to the software. Some problems with speed and vertical maneuver modeling were identified during data analysis of the initial fast-time study results; these were corrected in a revised version of ACES/AAC. Other updates include enhancements and additional options, such as allowing all flights at or near an arrival fix to be treated as general en route traffic, or using estimated fuel burn as a resolution criterion.

The follow-up study by NASA/ARC examines the effect of increasing action time on maneuver efficiency[11]. Resolution Initiation Time (RIT) is defined as the time between the start of a resolution maneuver and predicted loss of separation and, as used in this study, is analogous to action time. Maneuver efficiency is measured in terms of time delay and fuel consumption. NASA/ARC's AAC Autoresolver algorithm is used to generate all possible resolutions for a detected conflict and record the optimal maneuver. This process is repeated at one-minute intervals starting at conflict detection and continuing until loss of separation. The resolutions maneuvers are not simulated, so the flight paths remain consistent. A 3-hour, NAS-wide scenario of 4,800 flights is simulated with no weather or flight path uncertainty.

For every optimal resolution maneuver recorded, the associated delay time and fuel consumption are compared against the RIT using regression analysis. One overall finding is that the slope determined from regression analysis is statistically significant and suggests that increasing RIT (issuing resolutions earlier) does decrease maneuver delay and fuel consumption. However, the magnitude of the effect is small- a 2 second decrease in delay or 3 pound decrease in fuel consumption for every minute increase in RIT. So, the impact reported by the follow-up study after corrections were made to the simulation software is smaller than that found in the initial study.

## V. Conclusion

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. [4] 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.

In conclusion, tools and methods were employed to simulate multiple forecast scenarios and airspace regions amounting to thousands of flights simulated. The study estimates the fuel consumption reduction 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 initial ACES/AAC study results, direct-to maneuvers provide the only consistent benefit as a function of action time. Following the correction of some modeling issues and general upgrades to ACES/AAC, the study by NASA/ARC found that the impact of action time was statistically significant, although smaller than the initial results.

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## References

1. Federal Aviation Administration, "NextGen Project Level Agreement: TBO - Conflict Resolutions Advisories - Voice and Datacomm," Research and Technology Development Office, NextGen and Operations Planning AJP-6, March 16, 2010.

2. Federal Aviation Administration, "TBO - Conflict Resolutions Advisories Benefits Plan, Version 0.1," ATO-P, FAA Simulation and Analysis Group, William J. Hughes Technical Center, October 1, 2010.

3. Federal Aviation Administration, "Interagency Agreement DTFAWA-09-X-80031 concerning Enhancement to ACES/AAC for Improved NEXTGEN Decision Support Tool Concept Development Capabilities, Acquisition and Business Services," AJA-484, FAA Headquarters, 800 Independence Ave. SW, Washington, DC, 20591, 2010.

4. Paglione, M. M., Santiago, C., Pankok, C. J., Jr., Young, C. M., and Oaks, R. D., TBO – Conflict Resolution Advisories: A Simulation to Evaluate the Benefits of Strategic Maneuvering, DOT/FAA/TC-TN11/4, U.S. Department of Transportation, Federal Aviation Administration, William J. Hughes Technical Center, Atlantic City International Airport, NJ 08405, June 30, 2011.

5. Erzberger, Heinz, "Automated Conflict Resolution for Air Traffic Control," 25th International Congress of the Aeronautical Sciences, 2006.

6. Erzberger, H, Todd A. Lauderdale, and Yung-Cheng Chu, "Automated Conflict Resolution, Arrival Management, and Weather Avoidance For ATM," 27$^{th}$ International Congress of the Aeronautical Sciences, 2010.

7. Eurocontrol Experimental Centre, "User Manual for the Base of Aircraft Data (BADA) Revision 3.8," EEC Technical Note/Scientific Report No. 2010-003, April 2010, http://www.eurocontrol.int/eec/public/standard_page/proj_BADA.html [cited March 7, 2011].

8. Oaks, R. D., Ryan, H. F., and Paglione, M. M., Prototype Implementation and Concept Validation of a 4-D Trajectory Fuel Burn Model Application, AIAA 2010-8164, American Institute of Astronautics and Aeronautics Guidance, Navigation, and Control Conference, August 2-5, 2010.

9. SAS Institute Inc., JMP® Software: Classic Design of Experiments, [Course Notes], Cary, NC, 2007.

10. SAS Institute Inc., Safeguarding the Skies, http://www.jmp.com/software/success/faa.shtml, [cited: February 28, 2011].

11. Santiago, C., and Pankok, C. J., Jr., "The Effect of Time Until Loss of Separation on Resolution Maneuver Efficiency," Preliminary Report, NASA Ames Research Center, Moffett Field, CA, 2012 (unpublished).