technical note

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

Mike M. Paglione
Federal Aviation Administration, AJP-661

Confesor Santiago
Federal Aviation Administration, AJP-661

Carl J. Pankok, Jr.
General Dynamics Information Technology

Christina M. Young
CSSI, Inc.

Robert D. Oaks
General Dynamics Information Technology

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Atlantic City International Airport, NJ 08405

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16. Abstract

This technical note documents a fast-time simulation study for the Conflict Resolution Advisories (CRA) Voice and Datacomm project specified in the NextGen Project Level Agreement (PLA) for FY2010. The study, conducted through a joint partnership between the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA), uses the Airspace Concept Evaluation System (ACES) air-traffic simulation model along with the Advanced Airspace Concept (AAC) autoresolver to quantify the benefits of strategic controller actions. To achieve this, four increasingly strategic conflict start times, referred to as "action times," were simulated using three different predicted future traffic levels (2018, 2020, and 2025) and three different Air Route Traffic Control Center (ARTCC) regions: east (Boston and New York), central (Chicago and Indianapolis), and west (Los Angeles and Oakland). In total, 36 treatment simulations and nine baseline simulations were modeled, resulting in 45 total simulations. Various system and flight performance metrics were examined and experimental design techniques applied to estimate the benefits associated with increasing strategic resolution maneuvering in context of all these factors.

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Executive Summary

In today's aviation system, human 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. If a controller determines an aircraft must be maneuvered, they advise the aircraft flight crew using two-way radio communications. Even with an anticipated growth in air traffic, today's high level of safety must be maintained and therefore the cost of separation management is expected to increase. Thus, advanced automation is required to aid the air traffic controller and mitigate these costs. One such advanced separation management function 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 in air traffic. Its Conflict Probe (CP) algorithm will not only detect potential separation violations, but it will also provide a rank-ordered listing of potential conflict resolution maneuvers. CRA is expected to improve operational efficiencies in terms of reduced maneuvering, increased use of fuel-efficient maneuvers, more direct routing, and timelier controller actions.

To support the cost benefit case for CRA, the objective of this study is to test 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 used as the study's simulation platform. Additionally, the Advanced Airspace Concept (AAC) package within ACES is used to simulate the separation management function and determine conflict resolution maneuvers. ACES provides the capability to simulate air traffic from departure airport to destination airport, while AAC detects aircraft-to-aircraft conflicts that violate the five nautical miles and 1,000 feet separation standard and generates potential resolution maneuvers for each detected conflict. Each of these potential maneuvers is generated to ensure a seven nautical mile and 1,000 feet of separation with all other aircraft for 12 minutes. From these resolutions, AAC implements the solution that adds the least amount of additional flight time to the maneuvered aircraft.

Experimental design techniques were employed to plan and synthesize the results of the simulation. This resulted in examination of several factors including forecasted traffic demands from years 2018, 2020, and 2025; three different airspace regions (east, central, and west); and an AAC configurable parameter called the resolution action time parameter. This parameter is the amount of time prior to the time of first loss of separation to implement the derived resolution maneuver. For example, a 5-minute parameter value forces a simulated conflict to be resolved five minutes before actual loss of separation. This parameter was set at 5-, 7-, 9-, and 11-minutes to reflect the change from the current more tactical approach used by controllers to the more strategic approach anticipated in the future.

Four key metrics were employed to estimate the benefits associated with more strategic maneuvering. The first three metrics or response variables include the percentage difference of fuel, flight distance, and flight time of a baseline flight without any maneuvers. The fourth metric is the estimated maneuver delay time associated with each resolution maneuver modeled. Simulation runs were made and several experimental models were fit to the results. Overall, when warning time is high the expected fuel consumption benefit is observed (i.e., the fuel consumption decreases as the action time increases) by approximately 0.3%. With smaller warning times, however, there is no evidence of the fuel benefit. When considering maneuver type, a decrease in fuel consumption is observed for direct-to maneuvers, while an increase is observed for vertical maneuvers. For both horizontal and speed maneuvers, the benefit is marginal. However, for maneuver delay time the benefit increases as a function of action time for all levels of warning time and maneuver types.

Finally, the study concluded with a detailed listing of several recommendations for subsequent simulation studies. This includes recommendations of enhancements to the ACES/AAC simulation model and internal aircraft fuel burn calculator used to estimate the fuel impact. It also includes additional suggestions on further validation and calibration of the simulation modeling. Overall, the study provides a detailed examination of the effects of strategic maneuvering in context of the multi-dimensional factors and documents an extensive methodology of simulation modeling, fuel burn estimation, and synthesis of results using experimental design techniques.

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1. Introduction

This Federal Aviation Administration (FAA) technical note documents a study identified in the NextGen Project Level Agreement (PLA) titled *TBO*[1] - *Conflict Resolution Advisories* - *Voice and Datacomm* [7]. The PLA provides the milestones and obligation plan for the FY2010 TBO - Conflict Resolution Advisories - Voice and Datacomm Project. This project includes the analysis, prototyping, and software development activities required to implement conflict resolution advisories. This introductory section presents the scope of this document, a brief background of the study, the benefits to be studied, the study's contributors, and the organization of the document.

1.1 Scope of the Document

This document describes a fast-time simulation study that supports this PLA [7]. This study specifically provides a benefit analysis comparing the current procedures for resolving aircraft-to-aircraft conflicts, which are more tactical, with the more strategic procedures envisioned to be used in the future.

1.2 Background for the Study

The FAA created the National Airspace System (NAS) to provide a safe and efficient airspace environment for the air transportation system in the United States. This includes all commercial, general civilian and military aviation. The NAS 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 a greater stress and perhaps to 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 an air transportation system meeting the nation's air transportation system's anticipated needs in 2025. Since its creation the JPDO has published an integrated plan [6] and documented a concept of operations [5] 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.

In the United States, the FAA is the single Air Navigation Service Provider (ANSP) that operates the key components of the NAS, such as Air Route Traffic Control Centers (ARTCCs) and Terminal Radar Approach Control (TRACON) centers. A key function provided by an ANSP is to ensure the safe separation of aircraft within the air transportation system. This separation management function remains much as it was when radar was first introduced to civil aviation in the late 1950s. Aircraft-to-aircraft separation is managed by human 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 via very high frequency (VHF) radio. Although more recent automated decision support tools (DSTs) have been made available to controllers that predict potential loss of separation (i.e., conflicts) and aid in their evaluation, the effectiveness of the DSTs is limited by airspace complexity, controller workload, and the use of 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 DSTs that not only predict future conflicts, but also provide conflict resolution that is

1 TBO refers to Trajectory Based Operations.

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.

A specific separation management problem is an aircraft-to-aircraft conflict, which can be defined as a situation where two or more aircraft violate minimum separation criteria. The separation criteria depends on the aircraft's navigational equipment and the airspace (e.g., En Route, Terminal, or Oceanic) in which they are flying. For example, in En Route airspace the separation criteria may be five nautical miles horizontally and 1,000 feet vertically. A Conflict Probe (CP) is a DST that predicts when conflict situations may occur by continuously comparing projected aircraft positions over a user-specified look-ahead time.

Figure 1 presents a horizontal view of an example conflict situation in which an aircraft, identified as AAA001, is flying southbound under the control of the Sector A controller. Another aircraft, identified as BBB002, is flying eastbound at the same altitude under the control of the Sector B controller. In this figure the airplane icons represent the positions of these aircraft at 14:00 UTC[2], when a CP might predict a conflict in Sector A where their paths cross. The two aircraft are predicted to violate their separation criteria at 14:20 UTC, indicating a look-ahead time of 20 minutes. The situation is further complicated by the proximity of the aircraft to the sector boundary, in that the anticipated hand-off between the air traffic controllers would occur at about 14:16 UTC. This figure shows a typical separation management problem in which the flight path of the affected aircraft must be changed by heading, altitude, or speed changes.

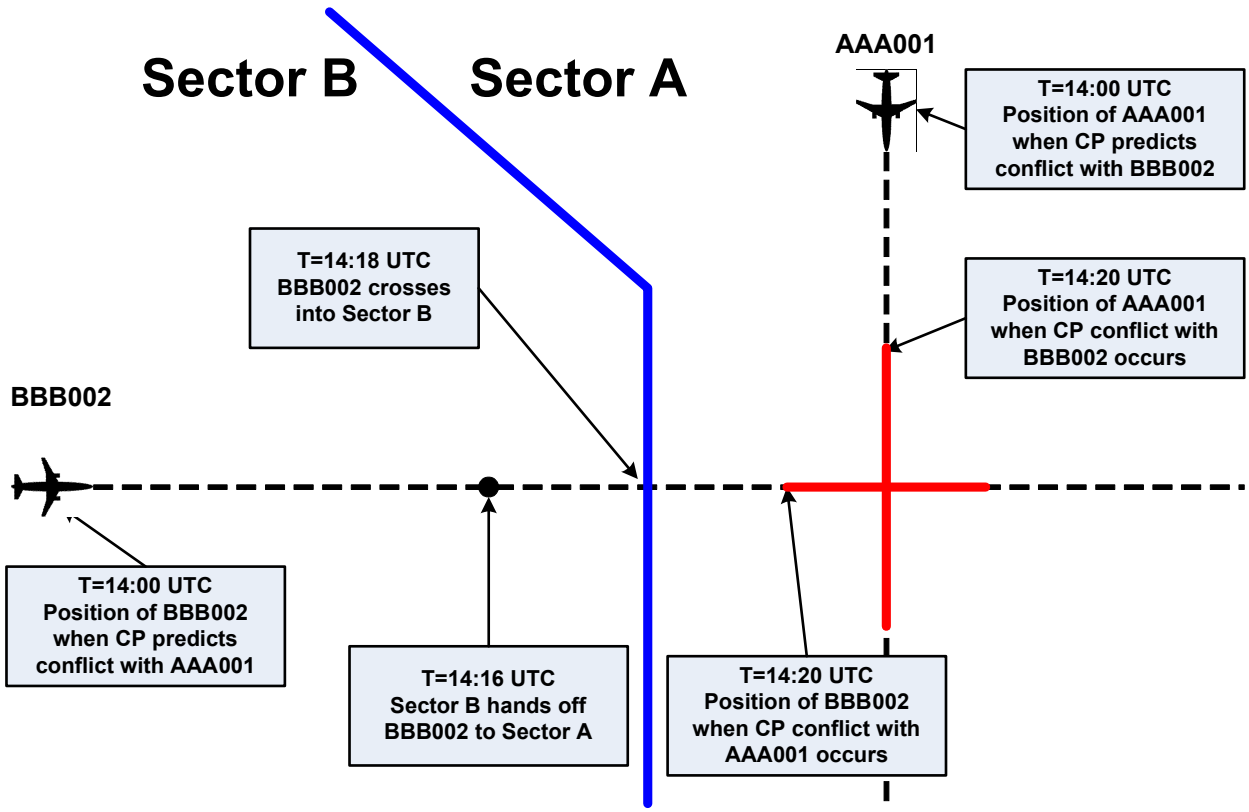


Figure 1: Illustrative Example of a Conflict

2 UTC refers to Coordinated Universal Time, which within this study is equivalent to Greenwich Mean Time

It must be emphasized, that this figure is presented for illustrative purposes only in order to provide a touchstone for describing how conflicts are resolved. The separation of aircraft is complex because each situation presents unique circumstances, where numerous variables such as other air traffic, special use airspace that must be avoided, proximity of one of the aircraft to its destination, weather, and controller workload influence the action selected by the air traffic controllers. For this reason a number of assumptions are made to simplify this example. First, it is assumed both AAA001 and BBB002 are mid-flight and at their cruise altitude and AAA001 is flying at a slower rate of speed than BBB002. Secondly, it is assumed there are no thunderstorms or other abnormal weather conditions nor any other aircraft in the area.

Lastly, it is assumed the CP presents the potential conflict to the Sector A controller. Given these assumptions, this is a simple conflict with few complicating factors that can be used in this Study Plan to illustrate approaches to conflict resolution. With this in mind, here is a comparison of the current and envisioned future ways that this conflict might be resolved:

- **Current Resolution of Conflicts.** In today's NAS there are a number of alternative ways to solve this illustrative conflict; none of which would be considered the "right" way to resolve the conflict. For example, since the Sector A controller is notified of the potential conflict by the CP he/she would typically call the Sector B controller and request an early hand-off of aircraft BBB002. Once the hand-off has occurred and BBB002 has established voice communications with the Sector A controller, the Sector A controller would notify the pilot of the heading change and the conflict would be avoided. Alternatively, the Sector A controller could contact the Sector B air traffic controller and have him/her initiate a heading change to BBB002 to resolve the conflict in a timelier manner. On the other hand, if the Sector A controller's workload was heavy, he/she might request AAA001 to change their altitude, thus avoiding the time consuming coordination with Sector B. With each of these alternatives there is much time lost due to coordination between sector controllers and voice communications with the affected pilots.
- **Future Resolution of Conflicts.** Since NextGen is currently in the process of defining the alternatives that will exist in the future NAS, it cannot be stated with certainty how this example conflict will be handled in the future. But it is anticipated the function of the CP will be enhanced to automatically take into account user preferences and aircraft capabilities to generate a rank-ordered set of resolutions that both resolve the conflict and meet metering constraints. The enhanced CP will then notify the Sector A controller of the predicted conflict and present a menu of recommended resolutions. The Sector A controller will identify the best resolution to the DST. If the best resolution involved maneuvering AAA001, automation would send the clearance directly to AAA001 via data link. However, if the best resolution involved maneuvering BBB002, the Sector B controller would be notified of the conflict and recommended resolution, and if the Sector B controller concurs, automation would send the clearance directly to BBB002 via data link.

1.3 Benefit to be Studied

The fast-time simulation described in this study plan is a part of a larger study defined in the PLA [7]. This effort is further clarified in the *TBO - Conflict Resolution Advisories Benefits Plan* [8]. In these documents seven potential benefits were identified:

- **Benefit B1: Reduced delays due to increased sector capacity**
- **Benefit B2: Reduced maneuvering due to improved intent entry**
- **Benefit B3: Reduced maneuvering due to more strategic controller actions**,
- **Benefit B4: Reduced altitude restrictions**
- **Benefit B5: Reduced number of altitude capped flights**
- **Benefit B6: Reduced use of altitude for direction of flight (DOF)**
- **Benefit B7: Increased use of established direct routes between city pairs**.

The study described in this technical note uses a fast-time simulation tool to investigate Benefit B3: Reduced maneuvering due to more strategic controller actions. Benefit B1: Reduced delays due to increased sector capacity will be evaluated in other studies using human-in-the-loop simulations. It is expected that future fast-time simulation and/or engineering studies will address the remaining five benefits listed.

1.4 Contributors

The contributors to this study, who worked together under an FAA Interagency Agreement [9], were:

- The FAA Simulation and Analysis Team (AJP-661) located at the William J. Hughes Technical Center, Atlantic City International Airport, NJ, was responsible for the study design, making the simulation runs, performing the data analysis, and documenting the results.
- The National Aeronautics and Space Administration Ames Research Center (NASA/ARC) located at Moffett Field, CA, aided in the study by providing the fast-time simulation system used in the study. This is not the first time NASA/ARC and AJP-661 have worked together on previous studies, so the familiarity between the teams made the study run smoothly.

1.5 Document Organization

This technical note is organized in the following sections: Section 2 describes the methodology used by this study; including the models and analysis tools, the overall design of the study, the metrics used in the study, and identifies the study's assumptions. Section 3 describes the analysis done for this study; including the data processing, the results, and the experimental design. Section 4 presents the study's conclusions. Section 5 presents recommendations for future studies. Section 6 presents a glossary of the acronyms used in this document. Section 7 contains the references cited within this document. Finally, Sections 8 and 9 contain supplemental appendices of various supporting tables and figures.

2. Study Approach

This section describes the various tools employed in the experiment. In addition, the overall design, the process flow, and the data used in the study are identified.

2.1 Models and Analysis Tools

This sub-section provides the detailed descriptions of the tools employed in the experiment.

2.1.1 Fast-time Simulation Tool

The Airspace Concept Evaluation System (ACES), a fast-time simulation tool developed by NASA/ARC, was used as the study's simulation platform. It has been used to simulate the NAS in current and proposed environments. In addition, the Advanced Airspace Concept (AAC) package within ACES was used to simulate the separation management function and determine conflict resolution maneuvers. This package works with ACES to provide an iterative approach, based on expert rules, to resolving conflicts in the NAS [2][3]. Collectively, ACES provides a capability where end to end air traffic can be simulated and AAC provides the ability to generate a list of resolutions for each conflict, then AAC implements the maneuver that resolves the conflict while adding the least amount of additional flight time. AAC detects conflicts that violate the five nautical miles and 1,000 feet separation standard, and produces resolutions with seven nautical mile and 1,000 feet of separation and conflict-free for 12 minutes.

This study used ACES to perform benefit assessments of current and future air traffic management concepts. Although ACES can include models of flights, airports, airspaces, air traffic service providers, flight decks, and airline operational control centers operating throughout the United States [21], in this study, ACES was used to generate realistic flight trajectories and AAC was used to deconflict these flights. Furthermore, in order to evaluate the benefit of resolution timeliness, resolution action times were configured at 5-, 7-, 9-, and 11-minutes.

In this study ACES takes input information adapted from flight schedules from a real 24-hour period and develops a realistic trajectory for each flight according to its flight plan. AAC makes its contribution when conflicts arise as a result of these trajectories. When it is discovered two flights will come into conflict, AAC analyzes the situation and attempts multiple resolutions to see which resolutions maintain the minimum separation required between the two aircraft. During this process, AAC also calculates the delay that would result from each resolution and chooses the resolution that contains the least amount of delay while still maintaining the minimum separation.[3] Theoretically, this process results in a 24-hour scenario where the total delay of the system is as small as possible. Finally, both ACES and AAC are equipped with a web application that displays charts, conflict geometries, and relevant figures associated with the simulated scenario. This application aided in the analysis phase of the study.

2.1.2 Scenario Generation Tools

AJP-661 developed tools to create the scenarios used for this study. Specifically:[4]

- ***ATOPScheduleToDB***: The FAA's Joint Planning Group (AJG) Forecast Schedules, which provided the air traffic demand used in this study (see Section 2.2.3), were provided in the form of ASCII files. *ATOPScheduleToDB* is an application that inserted this data into a table in the Oracle® database.

3 There are some cases where this is not true due to biases that make the ATC decision making more realistic.

4 Since the FAA's Advanced Technologies and Oceanic Procedures (ATO-P) provided the source files containing the forecasted air traffic demand, AJP-661 referred to these files as the ATO-P or ATOP files. As explained in Section 2.2.3, these files were created by the FAA's Joint Planning Group (AJG). For this reason, in this document, they are also called the AJG Forecast Schedules.

- ***ATOPScheduleConverter***: The *ATOPScheduleConverter* is an application that generates an air traffic scenario from the Oracle® database table. The forecast air traffic demand scenarios are 24-hour scenarios representing air traffic over the entire Continental United States (CONUS) airspace. Since this study was concerned with air traffic traveling through specific ARTCCs (see Section 2.2.2), this application also filtered aircraft for specific geographic regions.

2.1.3 Fuel Burn Calculator

AJP-661 has developed an application called the *FBCEnhanced* that calculates the amount of fuel consumed by an aircraft during flight. This application has been used in other FAA simulation and modeling work. AJP-661 performed an experiment and published the results of evaluating the validity of the techniques used by the *FBCEnhanced* application through comparison against many hours of fuel burn metrics from the flight data recorder of an operational FAA test aircraft [14]. The *FBCEnhanced* is based upon the European Organisation for the Safety of Air Navigation's (EUROCONTROL) Base of Aircraft Data (BADA) model version 3.8 [4]. The required input *FBCEnchanced* uses for each flight to calculate fuel burn is the aircraft type, the desired cruise speed and altitude, the takeoff weight, the departure and arrival airports, and the flight plan route. For this study, the *FBCEnhanced* application was used to process the 4-D trajectory of every flight for all the simulation runs and generated the metrics associated with analyzing the effect resolving conflicts earlier has on the system's fuel consumption.

2.1.4 JMP

JMP® is an interactive data visualization and statistical analysis tool available through the SAS Institute.[5] AJP-661 has used JMP® successfully in many other studies [19][20]. It was used extensively for the data analysis for this study because of its ability to interface directly with AJP-661's Oracle® databases to provide data tables, graphs, charts, and reports and because of its ability to provide statistical analyses and modeling capabilities including support of the study's Design of Experiment (DOE).

2.2 Overall Design of the Study

Figure 2 presents a graphic depicting NAS as a process that is to be analyzed in this study. Its input consists of an Air Traffic Scenario and the output to be evaluated in this study consists of the fuel consumption, the aircraft Delay, the number of conflicts, the Conflict Density, the Resolution Options per Flight, and the maneuvers per Flight. These output metrics are defined in Section 2.3. Controllable factors, which are also input to the process, are the year, the airspace region, and the action time. These are described in Section 2.2.2. As with all processes, there are also uncontrollable factors. Some of these are described in Section 2.5.

5 The SAS Institute Inc., SAS Campus Drive, Cary, NC 27513.

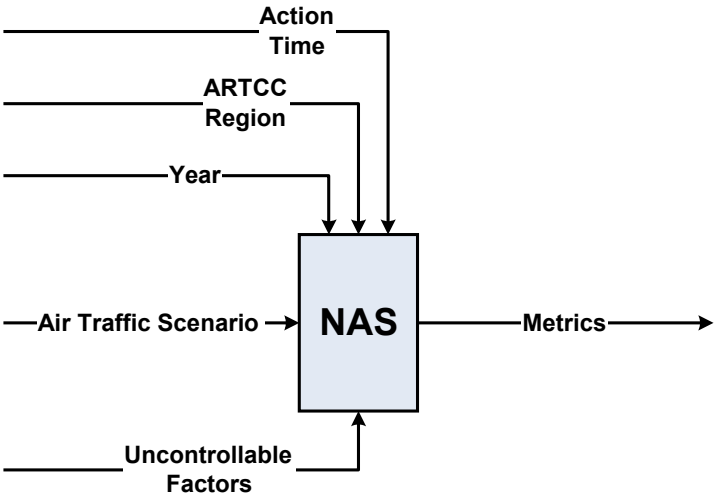


Figure 2: Model of the NAS Process Being Studied

The study itself was conducted using the processes and data shown in Figure 3. The data, represented by the rectangles, consists of Flight Data Set (FDS) Scenario Files, ACES Input Files, and Analysis Results; the processes, represented by the ellipses, consist of Run Scenarios and Analyze Data. The processes are described in Section 2.2.1. The data are described in Section 2.2.3.

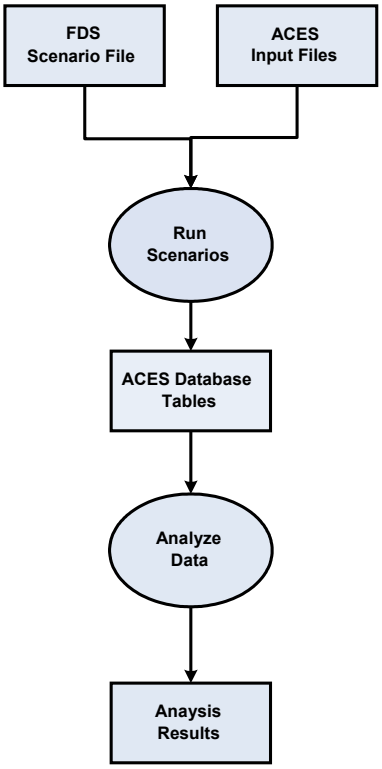


Figure 3: Study Process Flow

2.2.1 Study Processes

As stated in Section 1.3 this study addressed Benefit B3: Reduced maneuvering due to more strategic control actions as identified in the PLA [7] and summarized in the CRA Benefits Plan [8]. The assessment of this benefit was quantized using controlled experimentation techniques based on the DOE discipline. In addition, as stated in Section 2.1.1, the data required to assess these benefits was gathered using the detection and conflict resolution modeled by the AAC within ACES. In other words, with respect to Figure 2, ACES with the AAC package simulated the NAS process.

2.2.2 Controllable Factors

This study had three controllable factors: three forecast years, three airspace regions, and four action times. This combination of values for each of the three controllable factors resulted in a total of 36 simulation test runs (3 forecast years × 3 airspace regions × 4 action times). In addition, nine baseline scenarios runs were made representing the three forecast years and the three airspace regions. The conflict resolution logic was disabled in these nine runs, thus providing the trajectories and fuel burn when no deconflicting maneuvers were applied.

The purpose of these baseline runs is so that in each experimental treatment run the difference of each flight's fuel burn, flight distance, and flight times can be computed from the appropriate baseline run; obviously matching the flight, year, and region. The resulting difference represents the net fuel burn, flight distance, or flight time due to the maneuvers alone. Many flights may not have been maneuvered at all so it is expected many of these net differences would be zero. Only flights with some net difference had a maneuver but it is not guaranteed that the reverse is true, a flight that is maneuvered may still have a zero net difference (e.g. by chance the maneuver expended the same amount fuel as the baseline). These analysis processes are identified as Analyze Data in Figure 3.

2.2.2.1 Year

The air traffic scenarios used in this study were FDS files 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. These are described in more detail in Section 2.2.3.

2.2.2.2 Airspace Region

This study deals with conflicts identified in three pairs of adjacent ARTCCs. Each pair is referred to as a region and is selected based on operational conflict properties. The goal is to select center facilities with different characteristics, thus representing a wide range of air traffic operations.

To aid in this selection, an analysis was performed to categorize all ARTCCs based on conflict properties from daily operation and define clusters, or groupings of centers with similar characteristics. Some background information, including an overview of various conflict properties and their relevance, is provided in Ref. [16]. The five properties that are considered in this analysis are: vertical phase of flight, minimum horizontal separation, minimum vertical separation, encounter angle, and ratio of pop-up conflicts. These particular five conflict properties are chosen because they have been used in scenario generation in past studies; see Ref. [15]. For example, the count of pop-up conflicts per ARTCC is normalized by dividing by the total number of conflicts so the ratios can be compared across centers. For each of the five properties a metric is defined which measures the deviation of that property in a center from the average value of all centers.

Statistical cluster analysis is employed to quantitatively categorize these ARTCC's based on the normalized conflict properties. Cluster analysis seeks to define similar groups of entities based on their

characteristics. In this analysis, Ward's clustering method is performed in JMP® using the metrics for each of the five conflict properties. Three clusters are defined as a result, and one ARTCC is chosen from each cluster to provide a wide representation of conflict properties. An adjacent center is chosen for each to effectively create three distinct NAS regions. If a similar analysis is needed in the future, one enhancement would be to consider all combinations of adjacent ARTCC pairs and apply the clustering method described here to choose a pair (region) from each cluster.

The airspace regions were: Oakland (ZOA)/Los Angeles (ZLA), which is representative of the West Coast air traffic flow, Chicago (ZAU)/Indianapolis (ZID), which is representative of the Midwest air traffic flow, and Boston (ZBW)/New York (ZNY), which is representative of the East Coast air traffic flow. These airspace regions are shown in Figure 4.

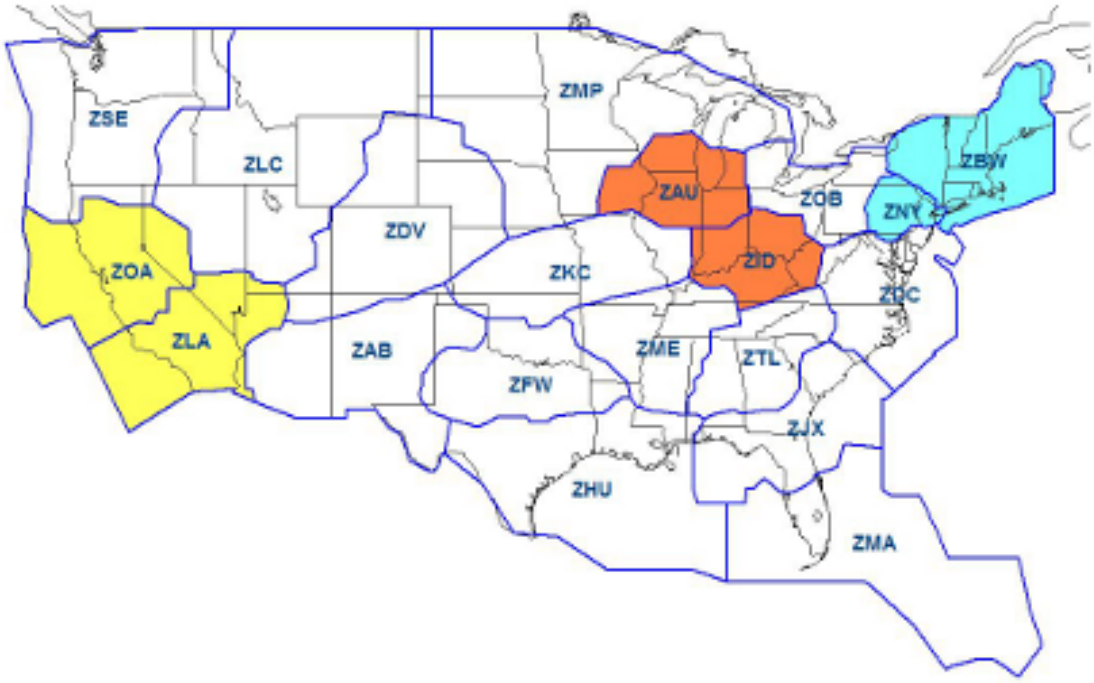


Figure 4: Airspace Regions

2.2.2.3 Action Time

As stated previously, the main purpose of this study is to investigate the effects of increasingly strategic resolution of conflicts. The level of strategy applied in different scenarios is captured by a single parameter- action time, which is used within AAC. The action time is the amount of time before an anticipated conflict at which AAC will implement a conflict resolution under normal circumstances. To help understand the action time parameter, the relationship between conflict detection time, resolution start time, and conflict start time is depicted in Figure 5. Note that resolution warning time is always limited by detection time.

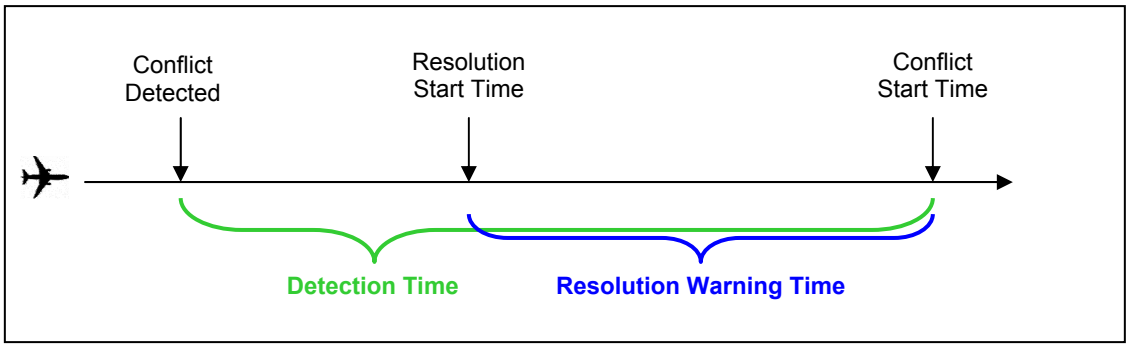


Figure 5: Conflict Detection and Resolution Timeline

Four action time values were used for this study: 5, 7, 9, and 11 minutes. Regardless of the value of the action Time parameter, AAC ensures the conflict pair will be conflict free for 12-minutes (a parametric value). Figure 6 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 start time) in four different scenarios applying the various action times.

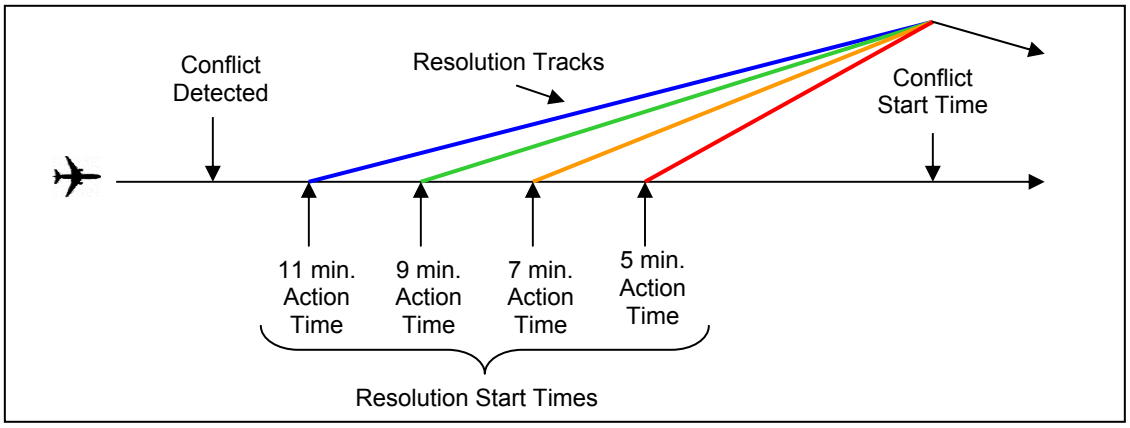


Figure 6: Action Time Definition- Large Detection Time

In Figure 6, 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 7, where a conflict is detected 8 minutes prior to its start time.

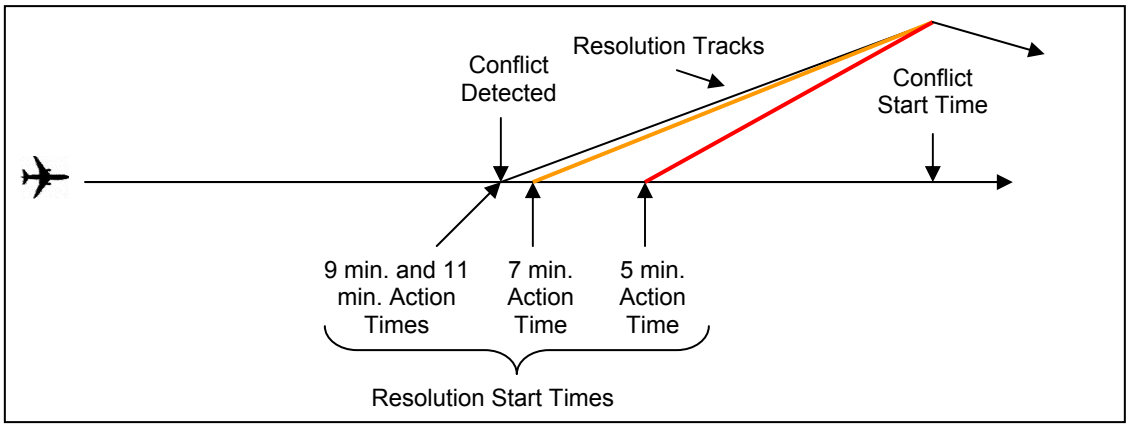


Figure 7: Action Time Definition- 8 Minute Detection Time

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, in which resolutions are implemented at the expected time points. A second special case is defined when a flight is within 20 minutes of its arrival fix. If a conflict is detected within this radius it is solved immediately, regardless of the specified action time.

2.2.3 Study Data

The study used AJG Forecast Schedules to estimate the air traffic demand. The AJG Forecast Schedules are 24-hour scenarios that include all flights arriving and/or departing within the specific 24-hour period. This means some flights in the scenario begin before the start of the 24-hour period and others end after the 24-hour period. These scenarios are based on recorded Enhanced Traffic Management System (ETMS) data and are representative of the number of flights listed in the FAA's Operations Network (OPSNET) for the day. Since ETMS data only shows Instrument Flight Rules (IFR) flights, a number of Visual Flight Rules (VFR) flights were added to accurately represent airport demand. The AJG Forecast Schedules are based on Terminal Area Forecast (TAF) and international growth rates, which were applied at the airport level and a Fratar Algorithm [12] was used to balance the network. To meet this expected demand in the scenarios, flights were cloned at the city-pair level and shifted in time plus or minus five minutes. The scenarios are made up of two days per quarter: one representing an offpeak day and one representing a peak day.

Table 1: Demand Level of the Three Years Used in the Study Based on 2009 Traffic

Year	Demand Level
2018	113%
2020	117%
2025	128%

For this study the forecast years were obtained from AJG Forecast Schedules based on the third quarter April 12, 2009 offpeak representative day, the traffic levels for which are presented in Table 1. As described in Section 2.2.2, the study used nine baseline scenarios based on the three years (2018, 2020, and 2025) and the three airspace regions (ZOA/ZLA, ZAU/ZID, and ZBW/ZNY). These nine scenarios were constructed using the three forecast years and filtering to include only those flights that flew through the airspace regions of interest. The number of flights that were extracted from these AJG forecast schedules for each of the nine scenarios is shown in Table 2. In addition, the scenarios were filtered to

remove the VFR flights, since the study was only concerned with En Route airspace, and to remove flights that had departure times in the previous day.

Table 2: Number of Flights for Each Scenario from AJG Schedule

Airspace Region	Year	Number of Flights
Central	2018	12,600
	2020	13,055
	2025	14,342
East	2018	12,074
	2020	12,544
	2025	13,871
West	2018	14,335
	2020	14,791
	2025	16,062

These nine baseline scenarios were converted to FDS files formatted as specified in the *ACES Software Users Guide* [18]. These files are identified as FDS Scenario File in Figure 3. Other input files used by ACES are also described in the *ACES Software Users Guide* [18]. These files are identified as ACES Input Files in Figure 3. The MySQL® database tables output by ACES are described in the *ACES Software Users Manual Appendix A – Messages* [17]. These tables are identified as ACES Database Tables in Figure 3. The study results, presented in this technical note, are identified as Analysis Results in Figure 3.

2.3 Metrics

This section details various metrics of interest presented in this technical note. Different metrics are used to express how strategic maneuvering affects the behavior and performance of the resolution function, individual flights, and the system as a whole. The following sub-sections describe metrics relating to conflict properties, resolution maneuver characteristics, and the performance of individual flights

2.3.1 Conflict Properties

The total number of conflicts is of interest. In addition, the following metrics are properties of individual conflicts and provide more detailed information:

- **Vertical phase of flight** denotes whether each aircraft of a conflict pair was in descent, climb, or cruise at the predicted conflict start time. These three categories result in six possible unique pairs.
- **Detection time** in seconds is the difference between conflict start time and the time the conflict is detected by the conflict probe, as illustrated in Figure 5.
- **Horizontal separation** of a conflict pair in nautical miles is calculated at the predicted time of first loss.
- **Conflict duration** in seconds is the period of time over which loss of separation is expected to occur without controller intervention and resolution.
- **Conflict density** is defined as the ratio of number of conflicts to number of flights. Note the expected number of conflicts for a flight to be involved in is twice the conflict density, because each conflict involves two aircraft.

It is anticipated the preceding metrics would vary across different regions in this study because the systems of simulated flights vary. The increase of traffic in future years is also expected to have an effect.

Finally, these conflict properties are affected by parameters of the conflict probe approach including look-ahead time and action time.

2.3.2 Resolution Maneuver Characteristics

The characteristics of resolution maneuvers are of even greater importance. The following metrics are recorded for each conflict and implemented resolution:

- **Maneuver type** indicates which resolution method was applied to resolve the conflict. The four types are: direct-to, horizontal (path-stretch or Parallel Offset), speed change, and vertical maneuver.
- **Number of potential resolution options** is the number of viable options available for resolution of a conflict.
- **Resolution warning time** in seconds is the difference between predicted time of first loss of separation and the resolution start time. This quantity is illustrated in Figure 5.
- **Maneuver delay** in seconds is the amount by which the remaining flight time is anticipated to increase when a given resolution maneuver is implemented. This value is calculated at the time of resolution.

These three metrics are closely related to the resolution method applied, and specifically the action time parameter.

2.3.3 Flight Performance Metrics

Finally, metrics that reflect the performance of individual flights can be combined to reflect the net impact on the system. The following metrics are recorded for each flight and may be averaged over all flights in a scenario for comparison to other scenarios:

- **Total fuel consumed** is the net fuel consumption over the portion of the flight path within the boundaries of the CONUS airspace.
    - **Percent difference in fuel consumed** from the baseline flight is also calculated.
- **Flight time** is the total time a flight spends in the CONUS airspace.
    - **Percent difference in flight time** from the baseline flight is also calculated.
- **Flight distance** is the total distance an aircraft flies in the CONUS airspace.
    - **Percent difference in flight distance** from the baseline flight is also calculated.
- **Number of conflicts** is the count of conflict events in which a flight is involved.
- **Number of maneuvers** to avoid conflict is the total number of times a flight is maneuvered over its entire path. A resolution may technically consist of multiple aircraft maneuvers, however, in this technical note we refer to the collection of maneuvers implemented as a resolution to avoid one conflict and rejoin the original flight plan as one maneuver.

The percent difference in fuel consumption, flight time, and flight distance from the corresponding value in the baseline run is calculated as [(treatment value – baseline value)/(baseline value)] × 100. Ratios of fuel consumption to flight time (in pounds per minute) and fuel consumption to flight distance (in pounds per nautical mile) are also considered. The metrics for individual flights are considered as the main response variables in the experimental design described in Section 2.4 and summarized in Section 3.2.2.1.

2.4 Experimental Analysis Plan

One of the most powerful inferential statistical approaches is the design, implementation, and synthesis of experiments. Experiments are performed by most researchers and scientists in practically all disciplines. An experiment is defined in Ref. [13] 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 Figure 8 presents the general model of a process under study as adapted from Ref. [13]. 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.

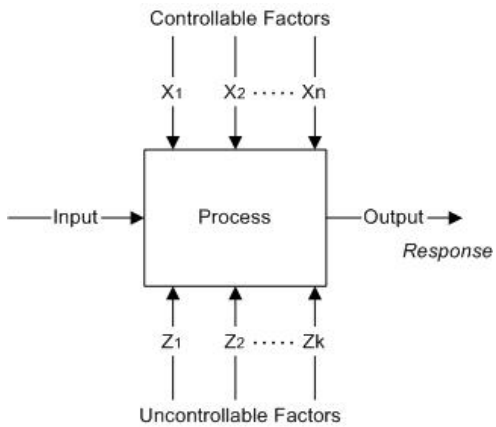


Figure 8: General Model of a Process (Adapted from Ref. [13])

Table 3: Processing Steps for the Experimental Analysis

Step	Description	Section
1	Define the problem statement	2.4.1
2	Design the experiment – The factors, levels of the factors, response variables to be run, and the model to be used for analysis are defined.	2.4.2
3	Execute the experiment and prepare output data – The simulation model is configured for the experimental runs defined by the design, runs executed, and resulting output data is processed for input into model (e.g. filter for outliers or data out of scope).	3
4	Implement statistical model defined by the experiment.	3
5	Synthesize results from the model and publish conclusions.	3

There are many purposes for performing an experiment. For this study, the objective of designing and executing an experiment is to determine (1) which pre-determined factors and interactions of these factors show a statistically significant effect on simulated flight performance, and (2) the relative sizes of the determined significant effects. From designing the experiment to concluding on its results, a series of processing steps should be performed as identified in Table 3. The first two steps presented in Table 3 are described in this section, which documents the plan for the experimental analysis. The last three steps are described in Section 3, which discusses the actual execution and analysis of the experiment.

2.4.1 Experiment Problem Statement

It was postulated that the CRA capability would allow air traffic control to maneuver aircraft more strategically. Thus, this simulation study needs to determine the impact of resolving potential aircraft-to-aircraft conflicts more strategically in the NAS. As already defined, initially there were three main factors in this study: (1) forecast years of aircraft traffic, (2) the en route airspace regions modeled, and (3) the strategic action time. The strategic action time is defined as the maximum time to resolve a conflict by the ACES simulation of the air traffic control function. It is a control parameter in the ACES simulation model that is being utilized to induce more strategic maneuvers. The impact is determined by the flight's performance in terms of net fuel expended, overall flight time, and flight distance traveled, as well as the delay time calculated at each resolution event.

The problem statement needs to concisely define the objective of the experiment. For this study it is expressed as follows:

> *"Through a set of simulation runs using the ACES platform, the experiment shall determine the statistically significant impact that longer action times has 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."*

The following sections describe an experimental design that aims at addressing this problem statement.

2.4.2 Design of the Experiment

As illustrated in Figure 8, the experiment needs to control the independent factors (controllable factors) and measure the dependent factors (response variables) while minimizing the effect of the uncontrollable factors. The latter are addressed typically by two techniques randomization or restriction on the randomization (e.g., blocking). The independent factors were already defined as the forecast year, airspace region, and action time. The response variables include the mean percentage of net fuel expended, flight time, and flight distance and the mean maneuver delay time in seconds. These metrics are defined in detail in Section 2.3.

An uncontrollable factor in this experiment was the actual warning time[6] of the conflict events. Initially during preliminary runs of the experiment, this factor was not considered at all and subsequently the analysis produced counterintuitive results. Through partitioning the resulting simulated conflicts into bins of warning time (i.e. restriction of the randomization), this factor was controlled and its effect was then studied along with the other three factors. Physically a conflict with a near term warning time would be limited in terms of strategic maneuvering while a farther term warning time would be ideal for strategic maneuvering. This is because conflicts need to be detected first and then resolved. Thus, it is expected that a strong interaction would exist between action time and warning time. This interaction is examined later with the results.

The experiment thus has four factors to examine with several levels defined for each. As listed in Table 4, forecast year was modeled at 2018, 2020, and 2025 traffic levels. The airspace was defined into three regions east, central, and west. The action times are modeled at four times in minutes. Thus, the first three factors produce 36 runs of the simulation model and the fourth factor partitions the conflicts into five bins from 0 to 11 minutes. This produces a total of 180 experimental runs to study.

Table 4: Summary of Experiment Factors and Levels

Description of Factor	Description of Levels	Number of Levels
Year (Y)	2018, 2020, and 2025	3
Airspace Region (A)	Airspace Regions: East, Central, West	3
Action Time (AT)	5-, 7-, 9-, 11-minutes	4
Warning Time (WT)	0-, 5-, 7-, 9-, 11-minutes	5
	Total Runs: $Y \times A \times AT \times WT =$	180

Since it is a fast time simulation study, the marginal cost associated with running individual runs is relatively low, so the full combination of runs was executed. The fuel burn, flight time, and flight distance

6 The actual or effective warning time is described in detail in Section 2.2.2.3.

is modeled by *FBCEnhanced*, a software application described in Section 2.1.3 that uses the resulting simulated trajectories output from the ACES model. In turn, the percentage net fuel burn, flight time, and flight distance is calculated by taking the difference of each treatment run minus a baseline simulation run where no maneuvering was modeled at all. The fourth response variable, maneuvering delay in seconds, is calculated internally by the ACES model at the implementation of each conflict resolution as the modeled delay associated to the particular maneuver.

Another consideration of the design is that a simulated flight may be impacted by zero, one, or more maneuvers associated with which it is involved. If a conflict exists for a flight, it may be chosen as one of two flights to be maneuvered to resolve the conflict. For the net flight metrics defined above, a flight with zero maneuvers is not of interest and should have a zero impact in the study. Flights that are maneuvered more than once would then have a cumulative effect on these metrics. However, it would be difficult and may be impossible to match the flight impact for each of these events separately using the current software. As a result, only flights with single maneuvers were selected for the designed experiment analysis. This still resulted in almost 61,000 flights to examine for the various runs being modeled.

Eq. 1 illustrates the mathematical model for this experiment. It 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 "μ"term.

Response:

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

Where:

Y_i = forecast years, i = 1, 2, 3
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, i

The model assumes the random error ($\varepsilon_{n(ijkl)}$) is independently normally distributed with a zero mean and that the various factors are linearly additive as illustrated in Eq. 1

There are four response variables and the same model in Eq. 1 addresses all four separately. Thus, the term, "R_{ijkl}," can refer to percentage of fuel impact, percentage of flight distance impact, percentage of flight time impact, and maneuver delay time. These response variables are calculated as means for the flights with single maneuvers (i.e. one conflict and one maneuver) for each of the various runs/levels defined in Table 4. The response variable then is an estimate of the expected value for each of these four output functions.

2.5 Study Assumptions

Some of the assumptions of the study include the following; many of these can be considered to be uncontrollable factors:

- AAC is assumed to be a reasonable approximation of a controller for the purposes of this study.
- No traffic flow management is used to condition flows in this simulation.
- Special Use Airspaces were not adapted for this study.
- Wake is assumed to be null, hence not modeled in this simulation study.
- Airports are simulated as sinks/sources with no assigned capacities.
- Weather was not considered in this study.
- ACES uses parameters derived from BADA to model aircraft performance. Over 200 different aircraft types are modeled in ACES using the BADA-derived parameters to calculate thrust, drag and fuel flow and to specify nominal cruise, climb and descent speeds. The four degrees of freedom specified in the model are the three-dimensional position in space as well as the aircraft roll to simulate turn dynamics.

3. Analysis

This section analyzes the results of the experiment whose approach is outlined in Section 2 of this report. First, in Section 3.1, the data is examined and any anomalies that do not represent the operational system are removed. This clean data is used in the subsequent analyses performed in Section 3.2, which delivers the results of the simulation study. Section 3.2 is composed of two general analyses: (1) System Performance which examines the conflict properties and the resolution maneuver properties and (2) Flight performance which examines various flight performance metrics as well as reports on the experimental design outlined in Section 2.4.

3.1 Preparation of Model Input and Output Data

This section describes the filtering mechanisms used to produce the most operationally-sound data possible for the experiment. Section 3.1.1 goes into detail about the process used to make the input traffic files compatible with ACES while Section 3.1.2 details the reasons why some flights were rejected by ACES. Sections 3.1.3 and 3.1.4 report the filtering methods performed on the ACES output data. Finally, Section 3.1.5 gives an overview of all of the filtering processes described in this technical note, as well as flight and conflict counts and how they differ between the original AJG schedule numbers and the final set used for the analyses.

3.1.1 Input Traffic File Filtering

The ACES input files were generated using the tools developed by AJP-661 and described in Section 2.1.2. Unfortunately, some of the information contained in the AJG Forecast Schedules was incompatible with ACES. AJP-661 developed an application named *FDSValidator* to resolve these issues. The specific problems were:

- Some of the aircraft types in the AJG Forecast Schedules were not contained in the *aircraft_characteristics_ds* table**,** which identifies the aircraft types that ACES models.
- Some of the airports in the AJG Forecast Schedules were not contained in the *terminal_model_management_ds* table, which identifies the airports that ACES models.
- Some flights in the AJG Forecast Schedules use only the departure and arrival airports to define the flight's route; and ACES requires at least three waypoints to define a route.

3.1.2 Rejected Flights

Table 5, Table 6, and Table 7 provide a summary of the traffic counts in each of the baseline runs in the central, east, and west airspace regions respectively. These tables show some flights were "rejected" by ACES due to modeling limitations. The ACES reasons for rejection are listed below as a matter of record, and have a negligible effect on the study:

- **En route portion of flight is international Crossings: 2 Entry: 0 Exit: 1** – This means the flight's departure airport is so close to the ARTCC boundary that the departure fix is in international airspace.
- **Intentionally filtering aircraft type** – These aircraft are: C17, F16, K35R, T34P, T38, and TEX2. The ACES input tables are set to exclude these aircraft.
- **Unknown aircraft type** – These aircraft are: A342, A345, B736, E500, G150, GL5T, HAWK, and T6. The ACES input tables are set to exclude these aircraft.
- **Unknown arrival/departure airport** – This airport was KGPI, which is Glacier Park International airport at Kalispell, MT; the *FDSValidator* application (described in Section 2.1.2) failed to map this to KFCA. This will be corrected for future studies.
- **Bad departure artcc index** – This is a situation in which the waypoints for a domestic flight were outside of the ARTCC boundaries.

- **Route not through one of the specified AAC Centers** – The *ATOPScheduleConverter* application (described in Section 2.1.2) should have excluded these aircraft, but did not. This was due to a difference in the boundary definitions in the *ATOPScheduleConverter* application and in ACES.
- **Trajectory contains anomalies** – This means the ACES trajectory generator was unable to model the flight profile because it was outside the aircraft's performance envelope.

Table 5: Summary of Baseline Central Runs

	2018		2020		2025	
Total FDS Flights		9566		9958		11060
En route portion of flight is international Crossings: 2 Entry: 0 Exit: 1	100		110		131	
Intentionally filtering aircraft type	13		13		13	
Unknown aircraft type	6		7		8	
Unknown arrival/departure airport	0		0		0	
Bad departure artcc index	11		12		12	
Route not through one of the specified AAC Centers	155		159		179	
Trajectory Contains Anomalies	0		0		0	
Rejected Flights		285		301		343
Active Flights		9281		9657		10717

Table 6: Summary of Baseline East Runs

	2018		2020		2025	
Total FDS Flights		8141		8511		9575
En route portion of flight is international Crossings: 2 Entry: 0 Exit: 1	190		209		263	
Intentionally filtering aircraft type	27		31		34	
Unknown aircraft type	18		17		19	
Unknown arrival/departure airport	0		0		0	
Bad departure artcc index	0		0		0	
Route not through one of the specified AAC Centers	388		405		466	
Trajectory Contains Anomalies	2		2		2	
Rejected Flights		625		664		784
Active Flights		7516		7847		8791

Table 7: Summary of Baseline West Runs

	2018		2020		2025	
Total FDS Flights		6790		7071		7897
En route portion of flight is international Crossings: 2 Entry: 0 Exit: 1	120		130		157	
Intentionally filtering aircraft type	24		24		25	
Unknown aircraft type	23		24		27	
Unknown arrival/departure airport	2		2		2	
Bad departure artcc index	5		5		7	
Route not through one of the specified AAC Centers	22		23		25	
Trajectory Contains Anomalies	1		1		1	
Rejected Flights		197		209		244
Active Flights		6593		6862		7653

3.1.3 Conflict Filtering

Whenever a conflict occurs, ACES outputs the conflict and various statistics associated with the conflict into a MySQL® relational database table. Therefore, each scenario produces its own set of conflicts to be analyzed. However, these conflicts need to be inspected for any unrealistic data that could not happen in the operational air traffic environment. The following list describes the filtering process in-depth. These steps are depicted in Figure 9.

1.) **Conflicts with Abnormally Large Negative Delays (Gains).** It was discovered that there were maneuvered flights that were unnecessarily increasing their speeds during a non-speed changing maneuver; this greatly decreased the delay and would not occur operationally. Therefore**,** all conflicts with a delay value less than negative eight minutes were removed (a value recommended by a NASA researcher who has used ACES for many air traffic simulation studies). This excludes any conflicts that are resolved using a direct-to maneuver; large gains for direct-to maneuvers are to be expected since the maneuvered flight is "cutting a corner" directly to a downstream fix.
2.) **Conflicts with Abnormally Large Delays**. Similarly, there were maneuvered flights that were decreasing their speeds during a non-speed changing maneuver and affecting the delay. For this reason, all conflicts with delay values greater than 20 minutes were removed from the conflict list. This value was decided on after discussions with researchers who are more experienced with the ACES modeling software.
3.) **Temporary Climb Maneuvers**. When validating the conflict data, there were many more temporary climb maneuvers with high values of delay than would be expected. Upon further investigation, a flaw in the way ACES models the maneuvered flights' trajectories was discovered. All conflicts that were resolved using a temporary climb maneuver and whose delay was either greater than one minute or less than negative five minutes were removed from the list.
4.) **Step Climb Maneuvers with Zero Delay**. From the remaining data, 4% of the conflicts reported a delay of zero minutes. Of these conflicts, 65% were resolved using a step climb maneuver. Theoretically, there should be very few resolutions that result in no delay, so the fact that there are so many of the same resolution type indicates that it is a result of a modeling error and not something that would occur operationally. After further investigation, all conflicts that were resolved using a step-climb maneuver with zero delay were removed from the list.

After applying these four filtering methods to the list of conflicts, a total of 3.4% of the original number of conflicts were filtered out of the data. The remaining conflicts represent the most realistic data that was output from the ACES simulations.

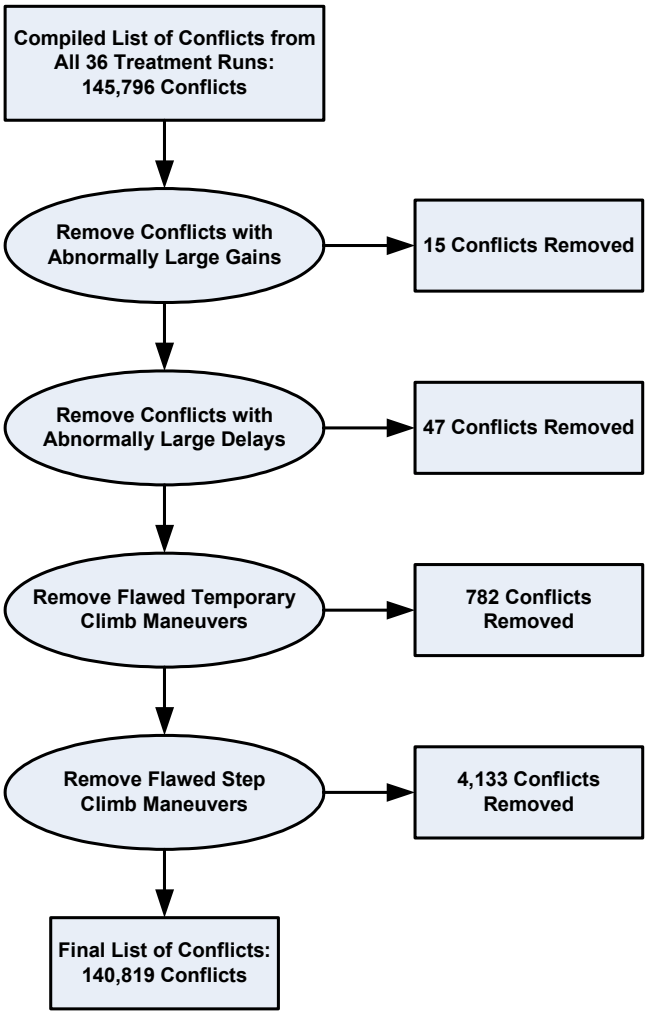


Figure 9: Conflict Filtering Process

3.1.4 Flight Filtering

After all of the ACES runs were completed and the *FBCEnhanced* application was run using the ACES output data, a list of every single flight from each of the 45 scenarios was compiled into one list. Figure 10 shows a flow chart of the filtering process used to filter down to the most realistic set of flights and more in-depth descriptions of these filtering methods follow the chart. The numbers of the descriptions correspond to the order of the filtering processes in Figure 10.

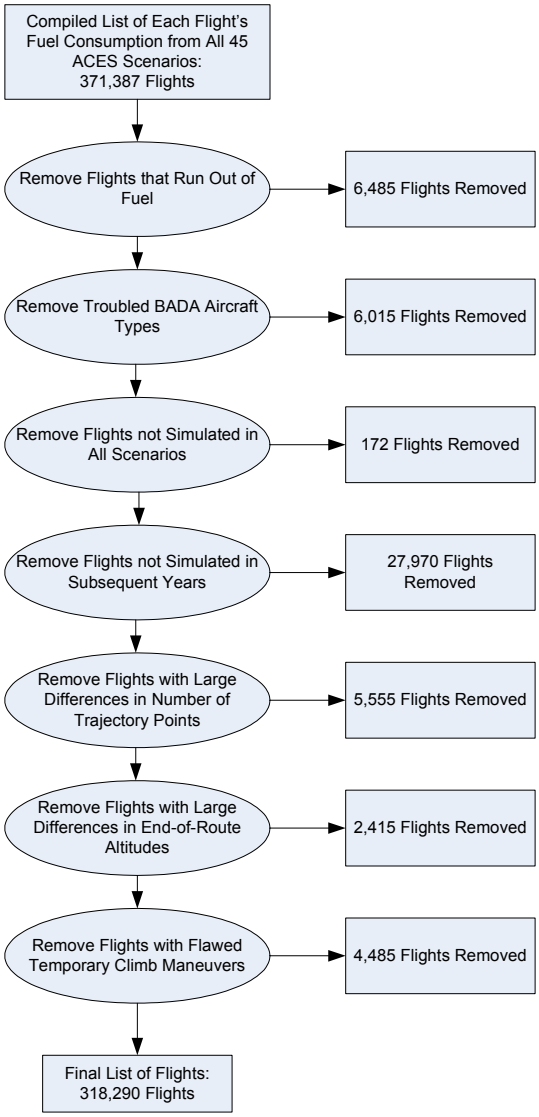


Figure 10: Flight Filtering Process

Before the process illustrated in Figure 10 commenced, the *FBCEnhanced* application dropped flights as it calculated fuel consumption. These flights were dropped for one of the following four reasons:

- Unrecognized Origin Airport
- Unrecognized Destination Airport
- Missing Flight Plan
- No Track Data
- Unrecognized Aircraft Type

When the ACES scenarios were done being simulated there were a total of 374,528 flights from all 45 scenarios. When the *FBCEnhanced* application completed, there were 371,387 flights remaining. This accounts for a decrease of 0.8% of flights. This list was then filtered further using the following methods:

1.) Flights that Run out of Fuel. The list of flights output by the *FBCEnhanced* application identified flights that ran out of fuel mid-flight. There are two main reasons these flights ran out of fuel. First,

there are some flights that were assigned incorrect altitudes. For example, there is a trans-Atlantic flight that is assigned an altitude of FL200. Any large jet assigned such a low altitude for a flight across the Atlantic Ocean would run out of fuel. The second reason for flights running out of fuel has to do with how the flights are modeled using BADA data. Some less-popular aircraft types are mapped to types whose performance characteristics are somewhat similar but not exactly the same. This can cause trouble in the estimation of takeoff weights, aircraft ranges, or maximum fuel capacity. These 6,485 entries can be attributed to shortcomings in the software, making them unrealistic and warranting their removal from the analysis.

2.) **Flights that Have Known Issues with BADA Aircraft Types.** The *FBCEnhanced* application has been used in many studies and through all of this experience, a list of BADA aircraft types with known issues has been compiled, shown in Table 8. All of these aircraft can be separated into six groups designated by the name in the column entitled "Aircraft Type," which lists the representative aircraft for the aircraft types listed in the right column. For example, BADA does not have a model for the aircraft type BE40 so the performance for this aircraft type is replicated by the performance model for a C560.

Table 8: List of BADA Aircraft Types with Known Issues

Group	Aircraft Type	Aircraft Mapped to "Aircraft Type" Performance
1	C421	[none]
2	C560	BE40, C56X, LJ24, F2H, MU30
3	H25B	H25A, C650
4	PA34	AC11, AC50, BDOG, BE35, BN2P, C310, C402, PA18
5	PAY3	AC90, AC95, C441, SW3, TBM7
6	PC12	[none]

Specifically, each group has its own, unique issues. For groups 1 and 2 in the table, the BADA range for these aircraft is only approximately half of their actual range. For group 3, the H25A aircraft type has a maximum takeoff weight of 4,000 pounds more than what BADA specifies and the C650 aircraft has a significantly greater range than the H25B, the aircraft to which it is mapped in the model. Finally, the BADA turboprop fuel burn model for groups 4, 5, and 6 only works within a certain range of speeds. For these groups, the PA34, PAY3, and PC12 aircraft types have a cruise speed that is outside of this range. All of these issues can be classified as software issues and any flights that have these aircraft types have been removed from the analysis data.

3.) **Flights that Are Not Simulated in all Five Scenarios of a Given Region and Year.** For each region-year entity, there are five scenarios: baseline, 5-minute action time, 7-minute action time, 9-minute action time, and 11-minute action time. It is expected if a flight is present in one of these scenarios, it should also be present in the other four scenarios that occur in the same region and year. If this requirement went unfulfilled, there would be scenarios of the same year-region pair where a flight is simulated in one but not another. This would negatively affect both the delay and fuel consumption statistics. Since the number of flights in a scenario is supposed to be an independent variable, any flights that did not meet this condition were dropped.

4.) **Flights that Are Not Simulated in Subsequent Years.** The AJG Forecast Schedules are set up so that increased traffic in future years is created by cloning flights that occur in the year on which the projected traffic level is based. For example, the scenarios simulated by ACES are based on traffic in 2009. In order to provide an increased number of flights in 2018, 2020, and 2025, random 2009 flights are cloned and no flights are removed. Therefore, if a flight is simulated in 2018 in the west region, it should also be simulated in 2020 and 2025 in the west region. As with step 3 previously, in an effort to keep the number of flights in the scenario as an independent variable (thus creating a controlled environment for the dependent variables), any flights that do not meet this condition were removed from the analysis.

5.) **Flights with Large Differences in the Number of Trajectory Points.** Two metrics created from the number of trajectory points produced by each flight were also investigated: the range of the number of points and the range divided by the mean number of points[7]. These metrics are referred to as the "range" and the "range-over-mean" metrics, respectively. Each flight within a region is simulated in five, ten, or 15 scenarios (5 action times × 3 years) and it is expected that the number of points for all of the scenarios should be within a reasonable range. Also, the range-over-mean metric is taken into account because when a flight produces more trajectory points, there are more opportunities for situations that would cause a change in the number of points. For example, a range of 20 points is far less significant for a flight that averages 500 trajectory points than it is for a flight that averages 50 trajectory points. After some consideration, it was decided a flight would be removed only if it fell in the upper 2.5% for both the range and the range-over-mean metrics. In terms of actual numbers, if a flight has both a range greater than 56 points and a range-over-mean greater than 0.14, the flight was removed from every scenario. The most significant cause for large discrepancies in the number of points resulted from ACES-simulated flights stopping a flight prematurely in one scenario but not in the others.
6.) **Flights with Large Differences in End-of-Route Altitudes.** Since ACES is known to stop simulating flights in mid-air, it is important to filter out these flights since their unrealistic fuel consumption numbers would negatively affect the analysis. For this reason, all flights with a range of end-of-route altitude in the upper 0.5% of the ranges are discarded. This means any flight with a range of end-of-route altitudes greater than 2,400 feet is removed from the analysis.
7.) **Flights with Flawed Temporary Climb Maneuvers.** Finally, all of the maneuvered flights that were filtered out of the conflict list as a result of Step 3 in Section 3.1.4 were removed from this flight list as well.

Upon completion of these filtering procedures, 14% of the flight entries that were output from the *FBCEnhanced* application were removed and 15% of the data output from the ACES scenarios themselves were removed. Using this filtering process yields the most realistic set of data and consequently allows for the best analysis possible. Unless otherwise noted, the data used in the analyses in the following sections is that which resulted from the two filtering processes described in Sections 3.1.3 and 3.1.4.

3.1.5 Scenario Properties

The data preparation process that started with the retrieval of the AJG schedule flights and ended with the post-simulation filtering processes removed roughly 60,000 flights from the data set. Table 9 shows how the number of flights in each scenario was affected by the data preparation. While the number of flights removed from the original AJG schedules may seem relatively large compared to the original number of flights, it is important to remember that approximately 75% of the flights that were removed were VFR flights, which would have had minimal effect on the study. Similarly, Table 10 shows how the data processing affected the number of conflicts in each scenario. The percentage of conflicts removed is not nearly as high as the percentage of flights removed because the conflicts were only processed through one set of filtering mechanisms whereas the flights went through multiple processes. Through the filtering methods presented in this technical note, a set of clean, realistic flights and conflicts was created that can be used to analyze the proposed changes to the system.

7 The term range, as used in this context, refers to the statistical range, which is the difference between the maximum and minimum values of a data set.

Table 9: Number of Flights for Each Scenario

Airspace Region	Year	Number of Unfiltered Flights	Number of Filtered Flights	Number of Flights Removed
Central	2018	12,600	7,708	4,892
	2020	13,055	8,361	4,694
	2025	14,342	9,690	4,652
East	2018	12,074	6,037	6,037
	2020	12,544	6,602	5,942
	2025	13,871	7,623	6,248
West	2018	14,335	5,285	9,050
	2020	14,791	5,695	9,096
	2025	16,062	6,657	9,405

Table 10: Number of Conflicts for Each Scenario

Airspace Region	Year	Number of Unfiltered Conflicts	Number of Filtered Conflicts	Number of Conflicts Removed
Central	2018	18,703	17,852	851
	2020	20,552	19,627	925
	2025	25,837	24,777	1,060
East	2018	9,754	9,572	182
	2020	10,631	10,445	186
	2025	13,141	12,905	236
West	2018	12,190	11,758	432
	2020	12,621	12,094	527
	2025	17,390	16,812	578

3.2 Synthesis of Model Output

These sections investigate the metrics presented in Section 2.3. As they are presented in Section 2.3, the metrics explained in this section are grouped into either system performance metrics or flight performance metrics. The raw data produced from the simulation can be found in Appendix B.

3.2.1 System Performance

When analyzing the benefits of a proposed change to the current airspace system, it is imperative to investigate certain metrics that represent how the system performed overall. These metrics are able to portray how the proposed environment compares to the current environment and are instrumental in quantifying the benefit of the proposed changes. The simulated system performance parameters presented in this section are grouped into two subsections: conflict properties and resolution maneuver properties. Section 3.2.1.1 focuses on the geometries of the conflicts themselves (before any action is taken to resolve them) while Section 3.2.1.2 focuses on the maneuvers that are used to resolve the conflicts and their effect on the system.

3.2.1.1 Conflict Properties

In this section, various conflict properties are presented along with their respective effects on the performance of the system. While these conflict properties are not significantly influenced by the changing action time parameter, they still have an effect on the system overall and thus should be investigated. The conflict properties that are explored in this section include the number of conflicts, vertical phase of flight, encounter angle, and the horizontal separation of the aircraft in a conflict. These investigations focus on how the maneuver delay is impacted by the geometry of a conflict. Additionally, every conflict property investigated in this section is distributed consistently with operational data [16]. This check provides further validity that the model is, in fact, producing realistic data.

In both Figure 11(a) and Figure 11(b), it can be seen that as the action time parameter increases, there is a slight increase in the number of conflicts regardless of whether it is grouped by region or year. Initially, it was assumed a larger action time would result in more efficient maneuvers and, consequently, fewer conflicts, but this figure shows this is not the case. Possible reasons for this are investigated and described in Section 3.2.2.2. As expected, a significantly greater number of conflicts occur in the 2025 traffic level than the other traffic levels because more flights are simulated in 2025. Additionally, the number of conflicts is appreciably greater in the central region than in the other regions because ZID and ZAU are at an intersection of flights heading north or south along the eastern seaboard and flights traveling east or west between the major cities of the east and west coasts.

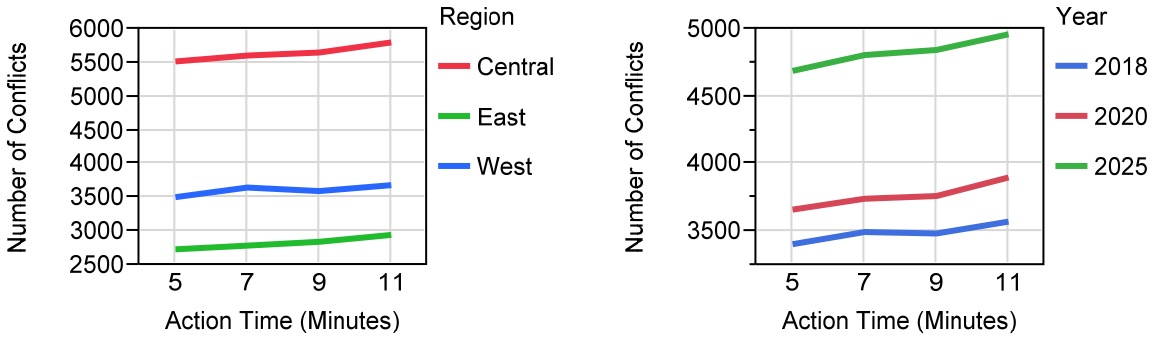


Figure 11: Number of Conflicts for Each Run Type: by Region and by Year

More conflicts occur in the west region than in the east region. The run summary tables in Section 3.1.2 show that for each year, the west region has fewer flights than the other two regions. This difference requires further analysis and is beyond the scope of this study.

The conflict density chart, depicted in Figure 12 shows the average number of conflicts per simulated flight separated by year and region. This calculation uses the number of flights that were modeled in the simulation (i.e. before the process described in Section 3.1.2). In the central-2018 scenario, for example, there are 0.525 conflicts for every flight that is simulated. In general, the central region has the largest conflict density followed by the west region and, lastly, the east region. The west region has a large amount of conflicts and a small number of flights, so it is expected that the west region's conflict density would be comparable to that of the central region, which has significantly more conflicts than either of the other two regions.

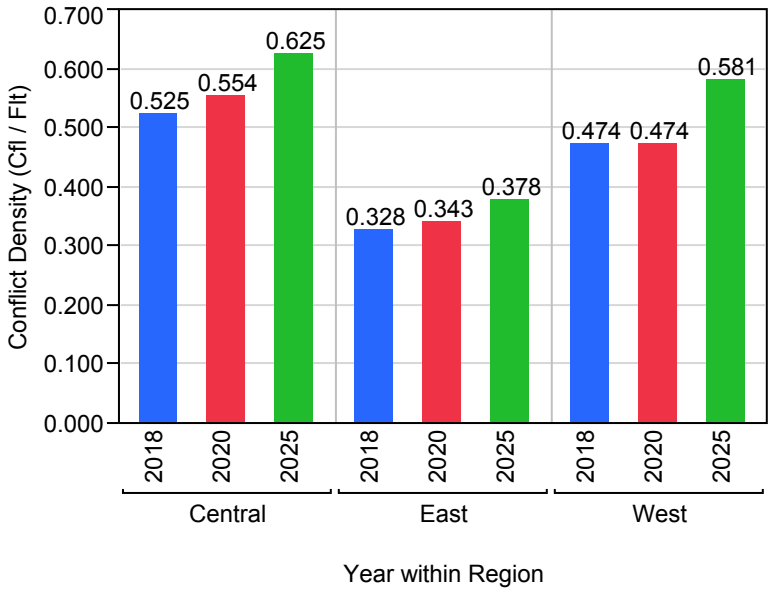


Figure 12: Conflict Density Chart Per Year for Each Region

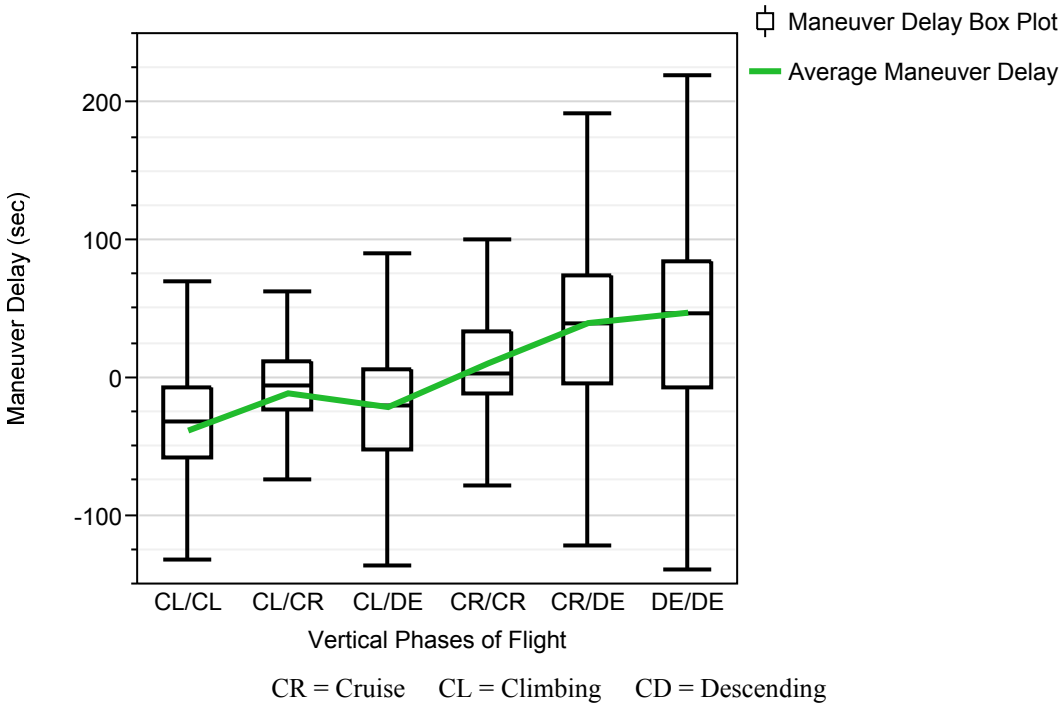
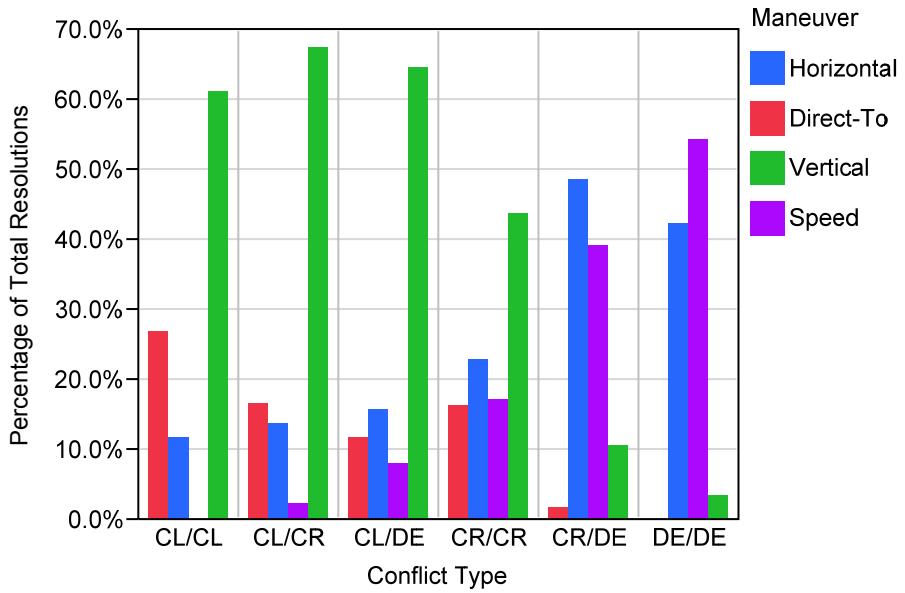


Figure 13: The Effect of Vertical Phases of Flight on Maneuver Delay



CR = Cruise CL = Climbing DE = Descending

Figure 14: Resolution Type Distributions by Conflict Type

Figure 13, which illustrates the delay based on the vertical phases of flight for the two flights in a conflict, shows, on average, a conflict involving two descending flights causes the most delay. Also, the chart shows when at least one flight is in descent, the variability of the maneuver delay is larger than for conflicts where neither of the two flights is descending. This is likely attributed to flights being spaced properly to land at their respective airports. To ensure proper spacing, flights in descent go through a variety of horizontal, vertical, and speed changes that increase the variability of the delay for these flights. Another interesting aspect of this data is that whenever at least one flight is climbing to its cruise altitude, the mean and median delays are both less than zero (i.e. there is a gain). Figure 14 shows when at least one flight in the conflict is climbing, a vertical resolution is used in more than 60% of the conflicts. Vertical resolutions tend to result in a delay close to zero, as investigated in Section 3.2.1.2. These conflicts also use a significant percentage of direct-to maneuvers to resolve conflicts, a maneuver known to result in great gains. These distributions are the greatest indicator as to why conflicts with one flight in ascent average gains rather than delays.

One metric that can significantly affect system performance is the encounter angle of the conflict which measures the difference in heading between the two flights. Figure 15 displays box-and-whisker plots that show how the encounter type (i.e. encounter angle bin) contributes to the maneuver delay. These three encounter angle groupings, which are adapted from Ref. 15, are illustrated in Figure 16. As shown in Figure 15, in-trail conflicts are the only encounter types that have a median maneuver delay not close to zero. The likely reason for this is that in an in-trail conflict, the flights are flying in the same direction, so their maneuvers take longer to complete, as shown in Figure 17. Since their conflict durations are much longer, the maneuvered flight is off of its cleared route for a longer period of time, resulting in a larger magnitude of delay.

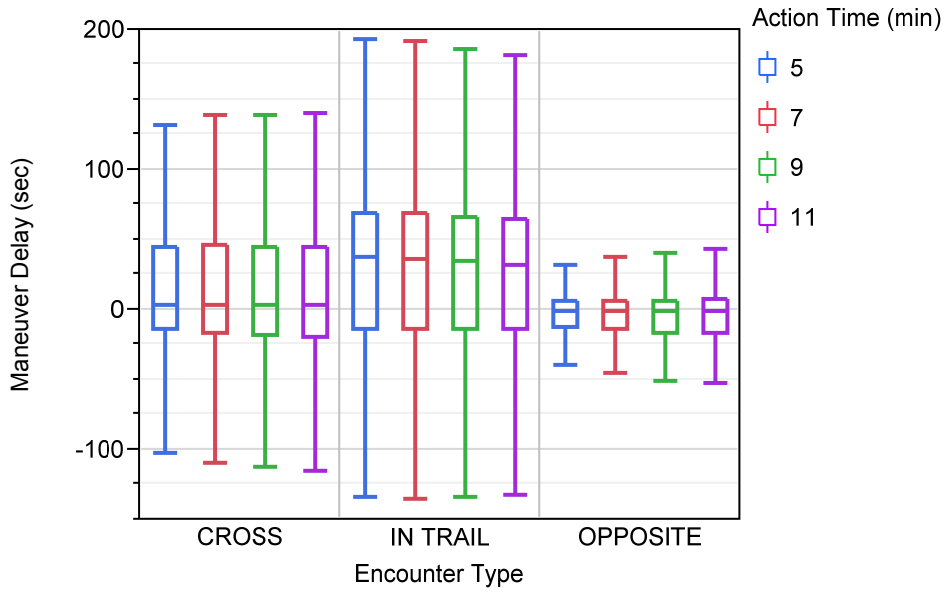


Figure 15: The Effect of Encounter Angle on Maneuver Delay

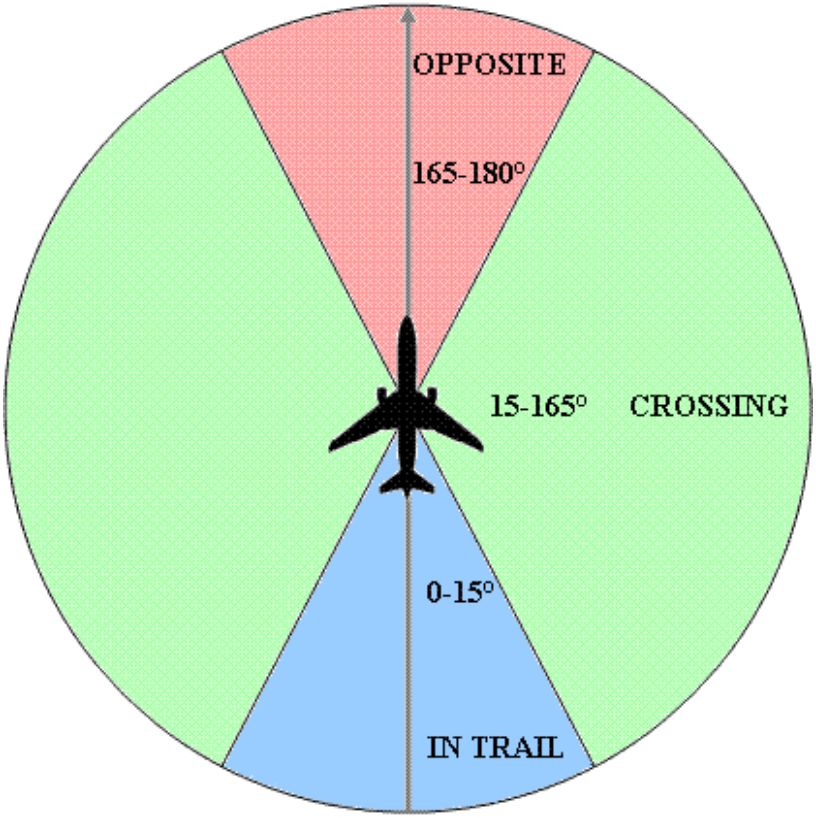


Figure 16: Encounter Angle Categories

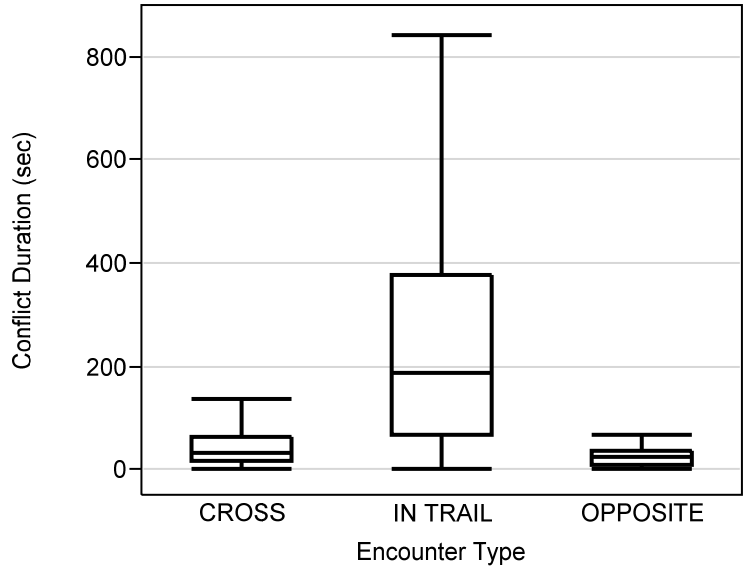


Figure 17: Conflict Duration for Each Encounter Type

Horizontal separation has a clear effect on delay in this simulated environment. In Figure 18, the horizontal separation on the x-axis represents the separation between the two flights if no resolution maneuver was instituted. As expected, the maneuver delay decreases as the horizontal separation increases. For example, if a flight is expected to come into conflict with another flight and their minimum separation is expected to be 4.5 nautical miles, less deviation from the cleared route is necessary than if the minimum separation is expected to be 0.5 nautical miles. This smaller deviation from the route results in a smaller amount of delay, a trend reflected in the chart. The data presented in Figure 18 verifies the expected performance of the model.

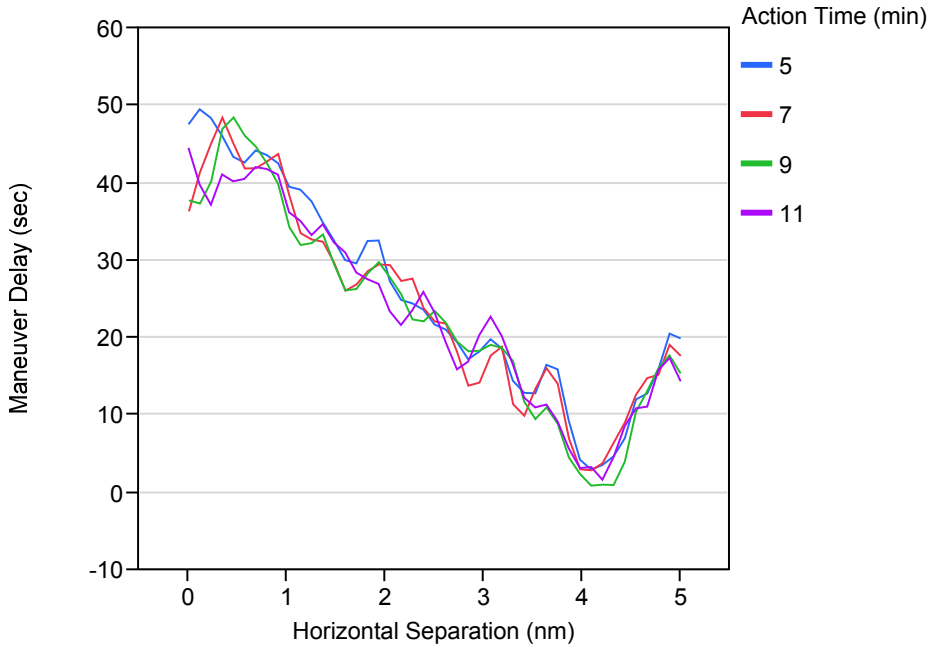


Figure 18: The Effect of Horizontal Separation on Maneuver Delay

Figure 19 shows the distribution of the detection time summed over all 36 treatment runs (defined in Section 2.2.2) and is representative of the distribution for each of the individual scenarios. Similarly, Table 11 reports some of the important statistics summarizing the detection time for each of the nine region-year entities of the scenarios as well as for the full data set. On average, the lowest detection times occur in the east region scenarios while the highest occur in the central region scenarios. Additionally, the mean detection time generally increases as the traffic level increases. For the data set overall, the mean detection time is almost 14 minutes, which is more than any of the action time parameters. Also, the histogram in Figure 19 shows that significantly more detection times fall in the 19-20 minute range than in any of the other ranges and that the minimum detection time for any of the scenarios is 65 seconds. The effect of these detection times and their relation to the action time parameter is investigated further in Section 3.2.2.2.

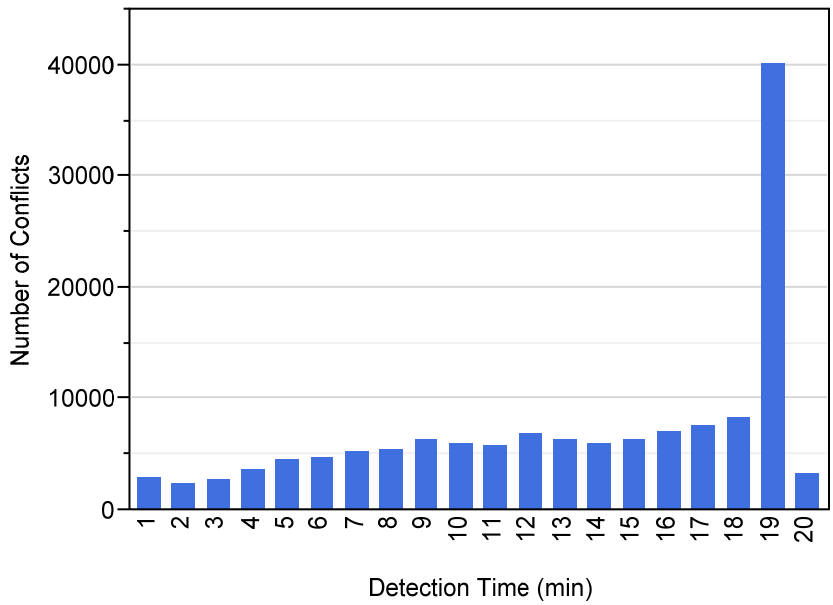


Figure 19: Histogram of Total Conflict Count by Detection Time

Table 11: Detection Time Statistics for Each of the Nine Region-Year Entities

Region	Year	Mean (min)	Std. Dev (min)	Median (min)	Quartiles (min)
Central	2018	14.53	5.08	15.83	10.50, 19.25
	2020	14.58	5.07	16.08	10.50, 19.25
	2025	14.64	5.03	16.08	10.67, 19.25
East	2018	12.40	5.96	12.83	7.17, 18.58
	2020	12.34	5.98	12.83	7.25, 18.50
	2025	12.58	5.84	13.00	7.67, 18.67
West	2018	14.00	5.64	15.75	15.75, 19.75
	2020	13.96	5.65	15.58	9.75, 19.25
	2025	14.26	5.49	16.00	10.08, 19.25
All Regions	All Years	13.93	5.50	15.25	9.58, 19.17

While the conflict properties are not significantly affected by the differing action times in these scenarios, they yield a deeper understanding of the system and provide insight to what factors affect the delay that results from conflict resolutions. Mostly, however, these metrics are used as a way to check that the simulated system is replicating the operational system as closely as possible (presented in Ref. [16]). Moreover, the understanding of the detection time and its distribution is vital in the inferential statistical analysis presented in Section 3.2.2.2. All of the statistics presented in this section show how the vertical phase of flight, encounter angle, and horizontal separation affect the delay of the system as well as how the detection time differs between traffic levels and regions.

3.2.1.2 Resolution Maneuver Properties

This section analyzes the maneuvers that are used to prevent a loss of separation between two aircraft. Some of these properties, like the number of options per conflict and system delay, change as a function of action time while others do not. Ultimately, the metric that gives the best indication of the resolution maneuver performance is the delay that results from these maneuvers. The material contained in this section analyzes how the maneuvers and the resulting delay affect the system performance.

Before ACES/AAC resolves a conflict, it attempts many resolution options and chooses the option that results in the least amount of delay; sometimes, up to 40 resolution options can be attempted to resolve a single conflict. However, not all of these resolution attempts are successful in resolving the conflict (e.g. a maneuver may not provide enough separation). Figure 20 depicts a chart, grouped by region, which shows how the average number of successful resolution options per conflict changes as a function of the action time. Initially, it was expected that as the action time increases, the number of resolution options would increase since there is more time between the maneuver start time and the loss of separation. There is a slight increasing trend in the data for each of the regions, but the lines are somewhat erratic. Regardless, the maximum range for any of the regions is 0.09 resolution attempts, which is insignificant compared to the average of approximately seven successful options per conflict. Therefore, these lines can be treated as being horizontal (i.e. consistent regardless of the action time).

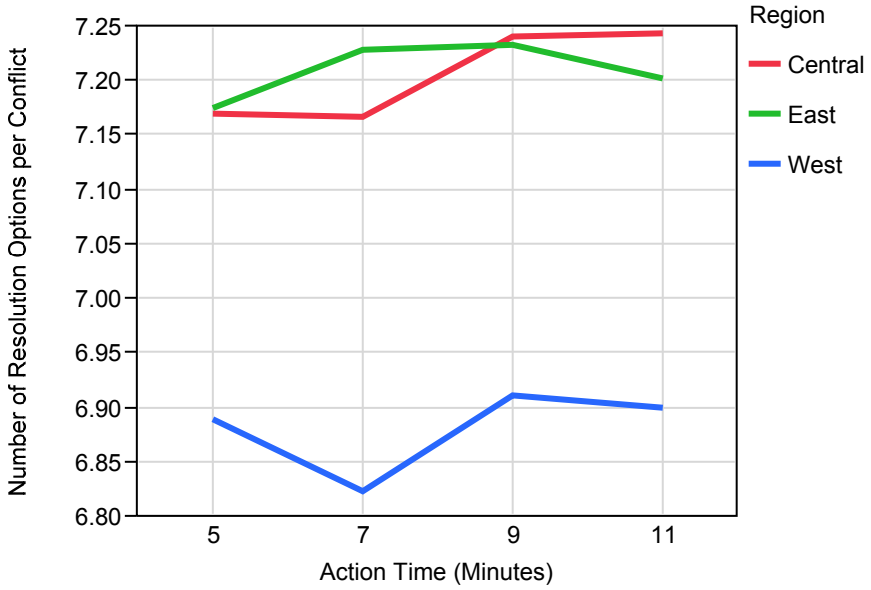


Figure 20: Average Number of Resolution Options for Each Region

Although the number of successful resolution options is not greatly affected by the magnitude of the action time, Figure 21 shows that the maneuver delay changes as a function of the number of successful options. Illustrated in the graph, as the number of successful resolution options increases, in general the average delay caused by a maneuver decreases. This result is intuitive because with more options available there is likely to be a resolution with a small delay. Also, the chart shows that after approximately eight options, the maneuver delay levels off to roughly zero delay for each of the four action time parameters. This figure shows that there is a negative correlation between the number of resolution options and the delay that results from instituting a maneuver.

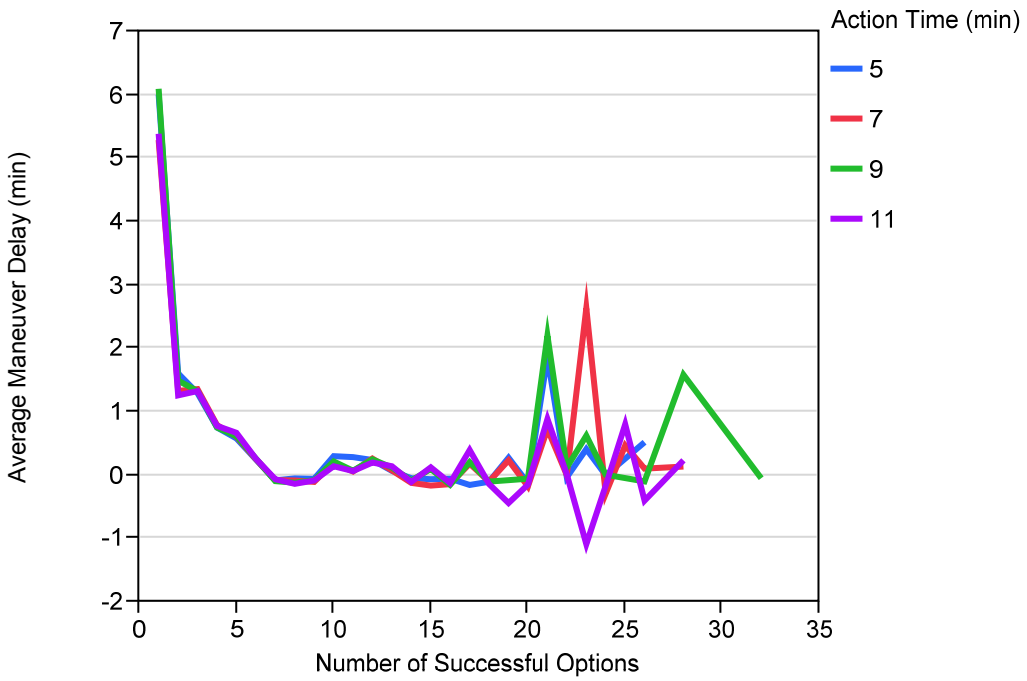


Figure 21: The Effect of the Number of Resolution Options on Maneuver Delay

Figure 22 shows the average distribution of resolutions used to resolve aircraft-to-aircraft conflicts for each region simulated in ACES. The distributions for the east and west regions are very similar while the central region differs from the other two in that a greater percentage of the resolutions are of the speed variety and less are direct-to maneuvers. Since the central region is, physically, the smallest of the three regions as well as the region with the most traffic, it is not unexpected that there would be a greater amount of speed resolutions. There is no deviation from the cleared route when a speed resolution is assigned, so in a region where space is already at a premium, the speed resolution becomes a very attractive maneuver option. Similarly, direct-to resolutions cause a greater deviation from the cleared route than any of the other resolution options, so while direct-to maneuvers have the potential to greatly reduce a flight's delay, the lack of physical space to conduct the maneuver makes it difficult to use a direct-to to resolve a conflict. Other than this difference in the percentage of speed and direct-to resolutions used, the data is consistent among the three regions.

Another aspect to consider is how much delay is caused by each resolution type. Figure 23 shows the box-and-whisker plots for the four types of resolutions and the black line shows the average delay that is caused by each. As expected, horizontal maneuvers produce the most delay of the four maneuvers while direct-to maneuvers cause the least amount of delay. Since the speed category encompasses both increases and decreases in speed, it has the largest delay range of the maneuvers shown in the figure.

While this figure does not reveal any metrics that are influenced by the action time, it is beneficial to break down the delay to understand the effect that each maneuver has.

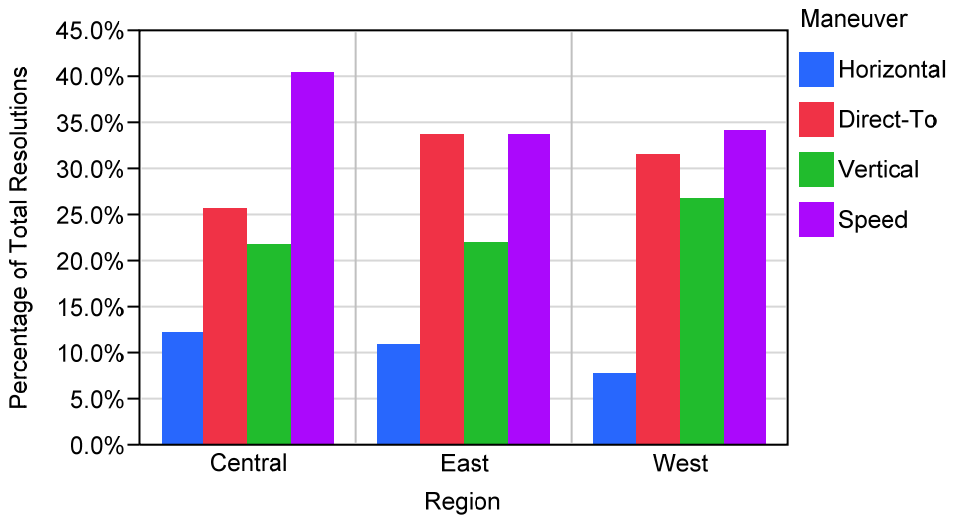


Figure 22: Resolution Type Distributions by Region

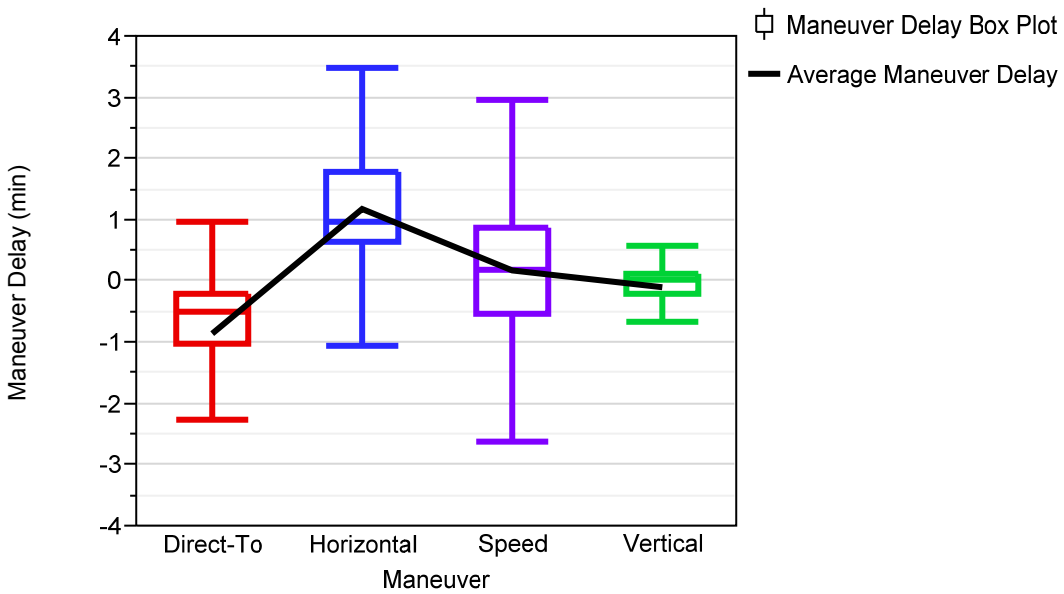


Figure 23: The Effect of Maneuver Type on Delay

Lastly, one of the most important system performance parameters to analyze is the delay in flight time that results from conflict resolution maneuvers in the system. Delay is measured as the amount of additional time added to a flight as a result of being maneuvered to avoid a conflict. Figure 24 shows the change in the delay as the action time increases, separated by traffic level. It is worth noting that the total delay in the system increases as the number of flights in the scenario increases (i.e. the year gets larger); this was a predictable trend in the data.

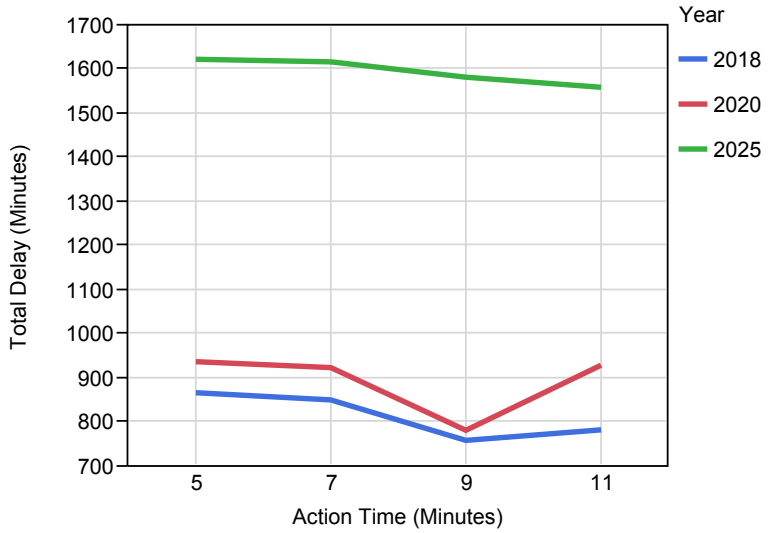


Figure 24: Total Delay Resulting from Conflicts by Traffic Level

At the beginning of the study, it was hoped that all three of the lines in the Figure 24 would display a steep downward decline as the action time increased. However, this is not the case in this figure; all three years show a slight decrease in delay, if any at all. Also, the same trend is displayed in Figure 25, which shows the average delay per conflict broken down by region and year. While these results may be somewhat discouraging, a greater understanding of the simulation and a deeper investigation into the data and the relationship between the resolution warning time and action time is needed before any concrete conclusions can be drawn. This investigation is expounded in Section 3.2.2.2, which goes into detail about the experimental design analysis of the study's benefits.

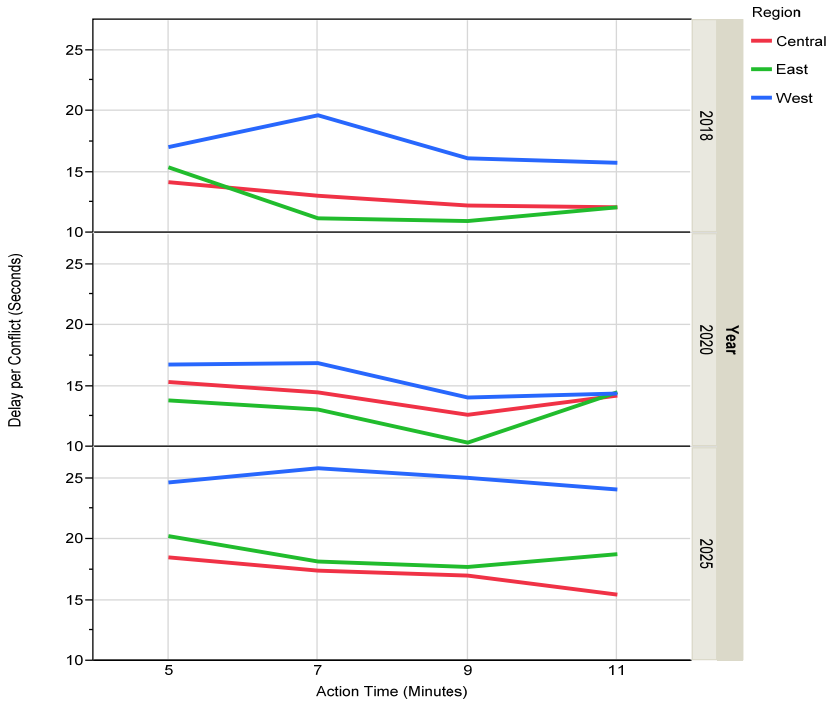


Figure 25: Average Delay Per Conflict

3.2.2 Flight Performance

The following two subsections provide a detailed synthesis of the results associated with the flights themselves as simulated in the experiment. Two main analysis approaches are provided. The first in Section 3.2.2.1 provides a descriptive statistical analysis of these flights with various statistical parameters presented. As described previously in Section 2.4, Section 3.2.2.2 provides a detailed inferential statistical analysis examining these same flights or a subset using inferential statistics (i.e. a multivariate regression model) to draw conclusions on the effects of specified modeling factors on a set of key response variables (e.g. action time impact on a flight's fuel burn).

3.2.2.1 Descriptive Statistical Analysis

This section presents an overview of the simulation results in terms of average flight performance. The average value of a metric is calculated over all flights in a given scenario of year, airspace region, and action time. For total fuel consumed, flight time, and flight distance, the percent difference from the same flight in a corresponding baseline run is calculated as [(treatment value – baseline value)/(baseline value)] × 100 for each flight, as stated in Section 2.3.3. Other metrics of interest are: ratio of fuel consumed to flight time, ratio of fuel consumed to flight distance, number of conflicts a flight is involved in, and number of times a flight is maneuvered. Table 12, Table 13 and Table 14 present the average values of these metrics for each of the scenarios in 2018, 2020, and 2025, respectively.

Table 12: Overview of Flight Performance Statistics for 2018 Scenarios

	Action Time	% Inc. Fuel Burn	% Inc. Flight Time	% Inc. Flight Dist.	Fuel/Time Ratio	Fuel/Dist Ratio	Number of Conflicts	Number of Maneuvers
East	5-min	0.18%	0.10%	0.15%	101.19	15.20	0.638	0.316
	7-min	0.17%	0.07%	0.11%	101.21	15.21	0.648	0.321
	9-min	0.15%	0.06%	0.10%	101.20	15.21	0.645	0.317
	11-min	0.19%	0.07%	0.11%	101.22	15.21	0.679	0.336
Central	5-min	0.01%	0.10%	0.13%	81.12	12.55	0.997	0.498
	7-min	-0.02%	0.06%	0.11%	81.13	12.55	1.014	0.504
	9-min	0.04%	0.08%	0.13%	81.15	12.55	1.031	0.512
	11-min	0.07%	0.09%	0.13%	81.16	12.55	1.045	0.522
West	5-min	0.08%	0.08%	0.13%	96.18	15.16	0.914	0.456
	7-min	0.12%	0.11%	0.16%	96.18	15.16	0.968	0.486
	9-min	0.14%	0.09%	0.15%	96.22	15.17	0.947	0.471
	11-min	0.13%	0.08%	0.13%	96.22	15.17	0.958	0.478

Table 13: Overview of Flight Performance Statistics for 2020 Scenarios

	Action Time	% Inc. Fuel Burn	% Inc. Flight Time	% Inc. Flight Dist.	Fuel/Time Ratio	Fuel/Dist Ratio	Number of Conflicts	Number of Maneuvers
East	5-min	0.14%	0.05%	0.15%	102.58	15.39	0.654	0.321
	7-min	0.15%	0.07%	0.14%	102.58	15.39	0.672	0.330
	9-min	0.18%	0.07%	0.15%	102.61	15.39	0.691	0.340
	11-min	0.17%	0.05%	0.13%	102.59	15.39	0.723	0.355
Central	5-min	0.03%	0.12%	0.16%	81.85	12.63	1.062	0.531
	7-min	0.03%	0.13%	0.15%	81.85	12.63	1.069	0.536
	9-min	0.04%	0.11%	0.15%	81.87	12.63	1.072	0.534
	11-min	0.08%	0.12%	0.16%	81.88	12.64	1.109	0.550
West	5-min	0.02%	0.08%	0.14%	97.38	15.36	0.921	0.458
	7-min	0.06%	0.09%	0.14%	97.40	15.36	0.945	0.473
	9-min	0.04%	0.09%	0.13%	97.39	15.36	0.939	0.469
	11-min	0.10%	0.08%	0.14%	97.44	15.37	0.957	0.477

Table 14: Overview of Flight Performance Statistics for 2025 Scenarios

	Action Time	% Inc. Fuel Burn	% Inc. Flight Time	% Inc. Flight Dist.	Fuel/Time Ratio	Fuel/Dist Ratio	Number of Conflicts	Number of Maneuvers
East	5-min	0.16%	0.13%	0.18%	104.00	15.59	0.726	0.362
	7-min	0.26%	0.11%	0.17%	104.19	15.62	0.744	0.369
	9-min	0.17%	0.15%	0.18%	104.03	15.60	0.769	0.381
	11-min	0.26%	0.13%	0.19%	104.14	15.61	0.782	0.386
Central	5-min	-0.02%	0.15%	0.19%	82.42	12.75	1.165	0.579
	7-min	0.00%	0.14%	0.19%	82.44	12.75	1.180	0.586
	9-min	0.04%	0.15%	0.21%	82.46	12.75	1.204	0.598
	11-min	0.05%	0.15%	0.21%	82.47	12.75	1.215	0.607
West	5-min	0.14%	0.16%	0.21%	97.43	15.40	1.103	0.546
	7-min	0.18%	0.18%	0.22%	97.42	15.40	1.134	0.561
	9-min	0.17%	0.15%	0.22%	97.44	15.40	1.125	0.558
	11-min	0.19%	0.17%	0.23%	97.45	15.40	1.171	0.581

Some general trends are visible, such as increasing number of conflicts with year. However there are several factors, including the controllable and uncontrollable factors discussed previously, that affect the average values and trends and confound the overall results for fuel burn and flight time. To account for these various factors and to be able to quantify the effect of action time, an inferential statistical analysis was performed using a designed experiment, described in the next section.

3.2.2.2 Inferential Statistical Analysis

In Section 2.4, an experiment analysis plan was presented that defined the inferential statistical approach being applied in this simulation study and provided a set of key processing steps planned for application of this approach. The first two were presented in Section 2.4, namely the problem statement was defined and the design of the experiment described, including a detailed multivariate regression model in Eq. 1. The results of implementing this approach are now presented in this section with the other results of the study. The execution and preparation of the data of the experiment is summarized in Section 3.2.2.2.1. Next, the statistical model is implemented in Section 3.2.2.2.2 and results synthesized in Section 3.2.2.2.3. Sometimes the synthesis of one experimental model may lead to the development of one or more additional models. For this study, an additional model is presented in Section 3.2.2.2.4, which drops one of the earlier less influential factors and examines a new factor.

3.2.2.2.1 Execution and Preparation of Data from the Experiment

As already discussed, the ACES simulation model is executed for the 36 treatment runs and flights with single maneuvers (one resolution applied per flight) were identified. Some flights were excluded for various reasons as defined earlier in the report (e.g. ACES modeling error for some international flights, fuel burn model missing aircraft performance model). Nine ACES simulation runs were run in addition to the 36 treatment runs for each year and airspace region level and conflict resolution is turned off. These nine runs represent the base runs and mapped to the 36 treatment runs to produce a total of 258,220 flights. The mapping is by flight id for a particular year and airspace region. Since only the flights with one maneuver are included this reduced to about 61,000 flights. Each of these flights then has a treatment run version of fuel burn, flight distance, and flight time and a baseline version of the same variables, where for the latter the flight flies the filed flight plan with no maneuvers or conflicts detected. The percentage difference between these two (treatment versus baseline) represents the percentage impact of the various treatment runs. For the forth factor, the actual warning time is partitioned by various bins (see Table 3). Next, the mean of the three percentage impact responses and the maneuver delay is calculated per run for all 180 runs defined in Table 3. The following section will synthesize the resulting means per run and apply them to the model defined previously in Eq. 1.

3.2.2.2.2 Implement Statistical Model

In Section 2.4.2 a specific experimental design was presented. As coded in Eq. 1 and described in Table 4, this proposed design is referred to as a full factorial design in the literature [1][11][13][19]. A full factorial design includes all possible combinations of factor levels in the experiment. It is expensive in terms of runs required but offers several advantages, especially early in the study of a process. In this study, the quantity of runs is relatively inexpensive because a fast-time simulation model is employed. Factorial designs may reveal the interaction effects of the factors under study, they are significantly more efficient than simple one factor at a time experiments, and the combinations of factor levels provide replications for evaluation of the individual factors, when some factors or factor combinations are removed from the experiment.

The full factorial experiment described in Section 3.2.2.2.1 was implemented and is summarized graphically in the following Figure 26, where leverage plots illustrate the actual and modeled values for each of the four responses. The top left cell contains data on the mean percentage fuel burn impact, top right the mean percentage of flight distance, bottom left mean percentage flight time, and bottom right cell the mean delay time in seconds. If the model could perfectly capture all the observed variation in the system, the actual measured response mean plotted on the y-axis in Figure 26 and the coincident modeled version on the x-axis would fall on a diagonal line perfectly. However, it is clear for all four responses the model does capture the trend and a reasonable percentage of the variation but is not perfect. The term

"Rsq" from Figure 26 plots is the coefficient of determination of the model.[8] This term provides a quantification of how well the model captures the observed variation in the system under study. For the four response variables under study in this experiment, the R^2 ranged from 0.55 to 0.73. In practical terms, this means that the model defined in Eq. 1 captured from 55 to 73 percent of the variation in the actual system under study. Further examination may reveal a better approach that will capture much more of the variation of the system.

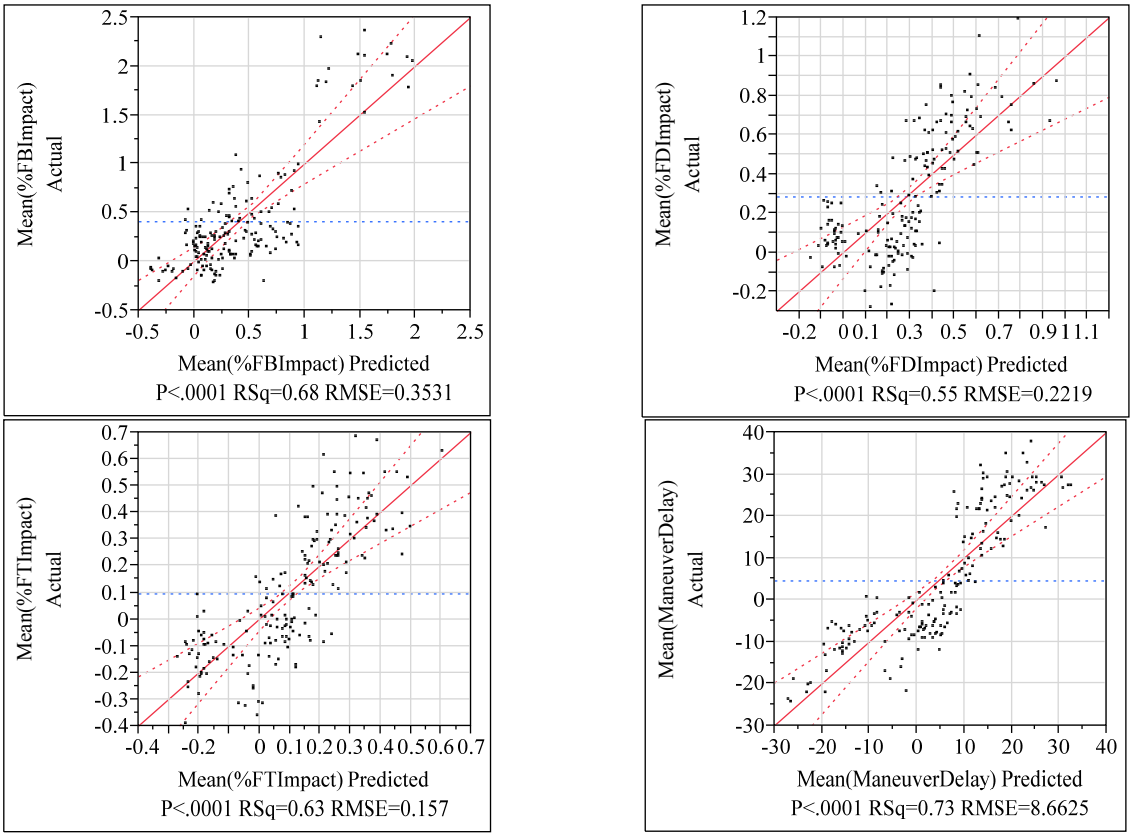


Figure 26: Full Factorial Leverage Plots per Response Result for Model 1

As stated earlier, the full factorial estimates the effects on number of factor combinations. For this study as expressed in Eq. 1, it models the main effects and the two-way interactions, three-way interactions, and four-way interactions. It would be useful to determine if all of these interactions are necessary in the model. A common approach is to only include the two-way interactions and use the others for replications in the experiment

Table 15 and Table 16 list the effect tests for the various factor level combinations of the experiment for percentage of fuel burn impact and maneuver delay time, respectively. The other two response variables will have similar results. For both these tables and shaded in blue, the three-way and four-way interactions are not statistically significant (p-value is greater than 0.05), providing evidence to drop these interactions out of the model and focus only on main and two-way interaction effects.

8 From Ref. [10] the R2 is the coefficient of determination and is equal to the ratio of the sum of squares of the model divided by the sum of squares of the total variation. The total variation equals the modeled variation plus the error in the model (estimated by calculating the difference between model and observed values).

Table 15: Model 1 Effect Tests for Percentage of Fuel Burn Impact Response Variable[9]

Source	DF	Sum of Squares	F Ratio	P-Value
Year	1	0.000782	0.0063	0.9370
Airspace Region	2	5.382674	21.5849	<.0001*
Year × Airspace Region	2	0.024440	0.0980	0.9067
Action Time	1	1.522910	12.2140	0.0006*
Year × Action Time	1	0.022812	0.1830	0.6694
Airspace Region × Action Time	2	0.207496	0.8321	0.4371
Year × Airspace Region × Action Time	2	0.008880	0.0356	0.9650
Warning Time	1	23.316181	186.9992	<.0001*
Year × Warning Time	1	0.000195	0.0016	0.9685
Airspace × Warning Time	2	5.954824	23.8793	<.0001*
Year × Airspace Region × Warning Time	2	0.035942	0.1441	0.8659
Action Time × Warning Time	1	4.627848	37.1160	<.0001*
Year × Action Time × Warning Time	1	0.000160	0.0013	0.9714
Airspace Region × Action Time × Warning Time	2	0.084671	0.3395	0.7126
Year × Airspace Region × Action Time × Warning Time	2	0.012029	0.0482	0.9529

Table 16: Model 1 Effect Tests for Maneuver Delay Time Response Variable

Source	DF	Sum of Squares	F Ratio	P-Value
Year	1	77.382	1.0312	0.3114
Airspace	2	7.481	0.0499	0.9514
Year × Airspace	2	169.205	1.1275	0.3265
Action Time	1	3441.928	45.8686	<.0001*
Year × Action Time	1	1.077	0.0144	0.9048
Airspace × Action Time	2	127.736	0.8511	0.4289
Year × Airspace Region × Action Time	2	3.158	0.0210	0.9792
Warning Time	1	27148.964	361.7989	<.0001*
Year × Warning Time	1	62.982	0.8393	0.3610
Airspace × Warning Time	2	917.543	6.1138	0.0028*
Year × Airspace Region × Warning Time	2	7.079	0.0472	0.9539
Action Time × Warning Time	1	369.281	4.9212	0.0280*
Year × Action Time × Warning Time	1	2.407	0.0321	0.8581
Airspace Region × Action Time × Warning Time	2	42.856	0.2856	0.7520
Year × Airspace Region × Action Time × Warning Time	2	13.451	0.0896	0.9143

9 The column labeled "Source" defines the particular effect produced from the combinations of factors listed. The column labeled "DF" is the degrees of freedom for the particular factor combination. The column labeled "Sum of Squares" is calculated by summing the squared differences of the observations minus the mean. The column labeled "F Ratio" is the test statistic produced by model mean square divided by the error mean square. The column labeled "P-value" is the probability that the test statistic is not significant. A p-value that is less than 0.05 is marked by an asterisk to indicate it provides evidence that the particular factor is statistically significant.

Therefore, based on the results presented in Figure 26, Table 15, and Table 16, the model was modified to include only the main effects and two-way interactions defined now as Model 2 in Eq. 2. Also, it was hypothesized that the action time and warning time factors may have non-linear effects on the response variables, as represented in the model by the AT × AT and WT × WT terms in Eq. 2.

Response:

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

Where:

Y_i = forecast years, i = 1, 2, 3
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*

For Model 2, the performance was significantly improved with R^2 results ranging from 0.68 to 0.85. This is illustrated graphically in the leverage plots in Figure 27, where the residuals were more closely following the diagonal lines drawn in the plots.

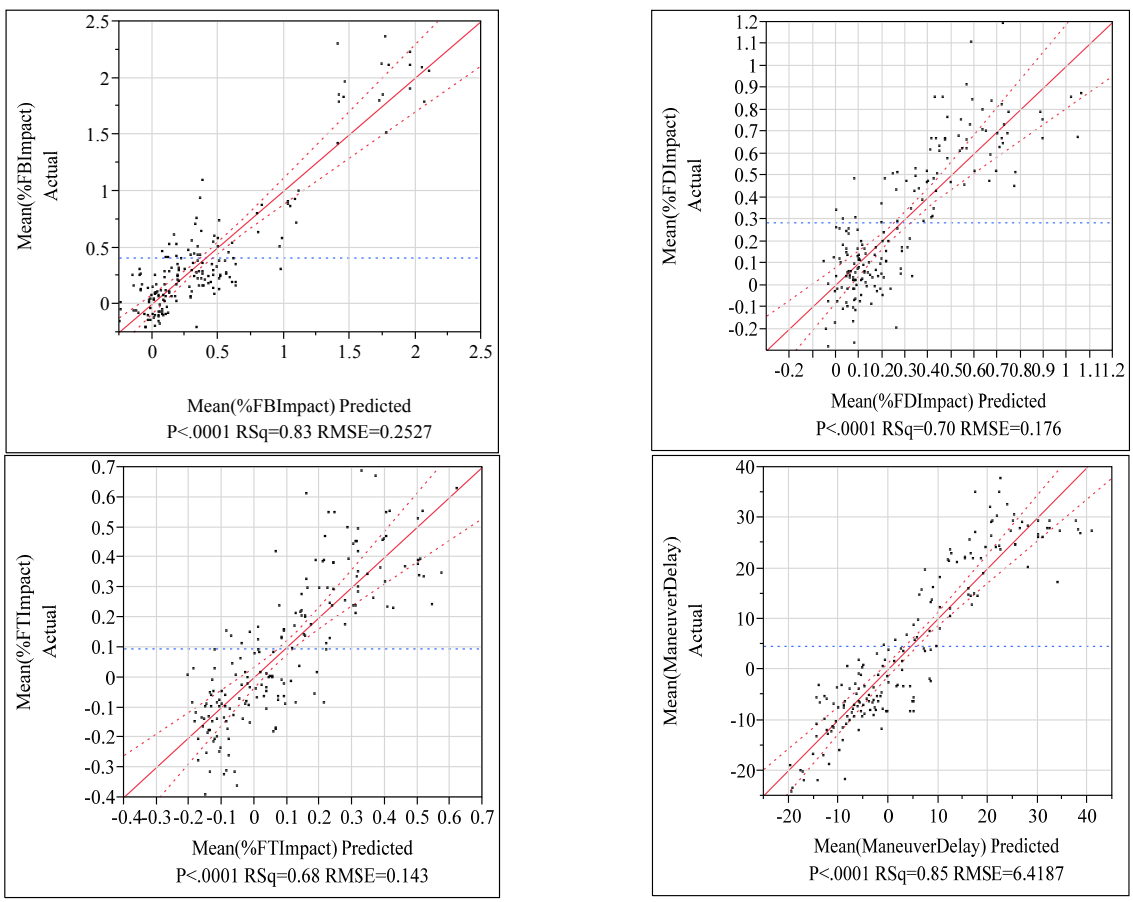


Figure 27: Full Factorial Leverage Plots per Response Result for Model 2

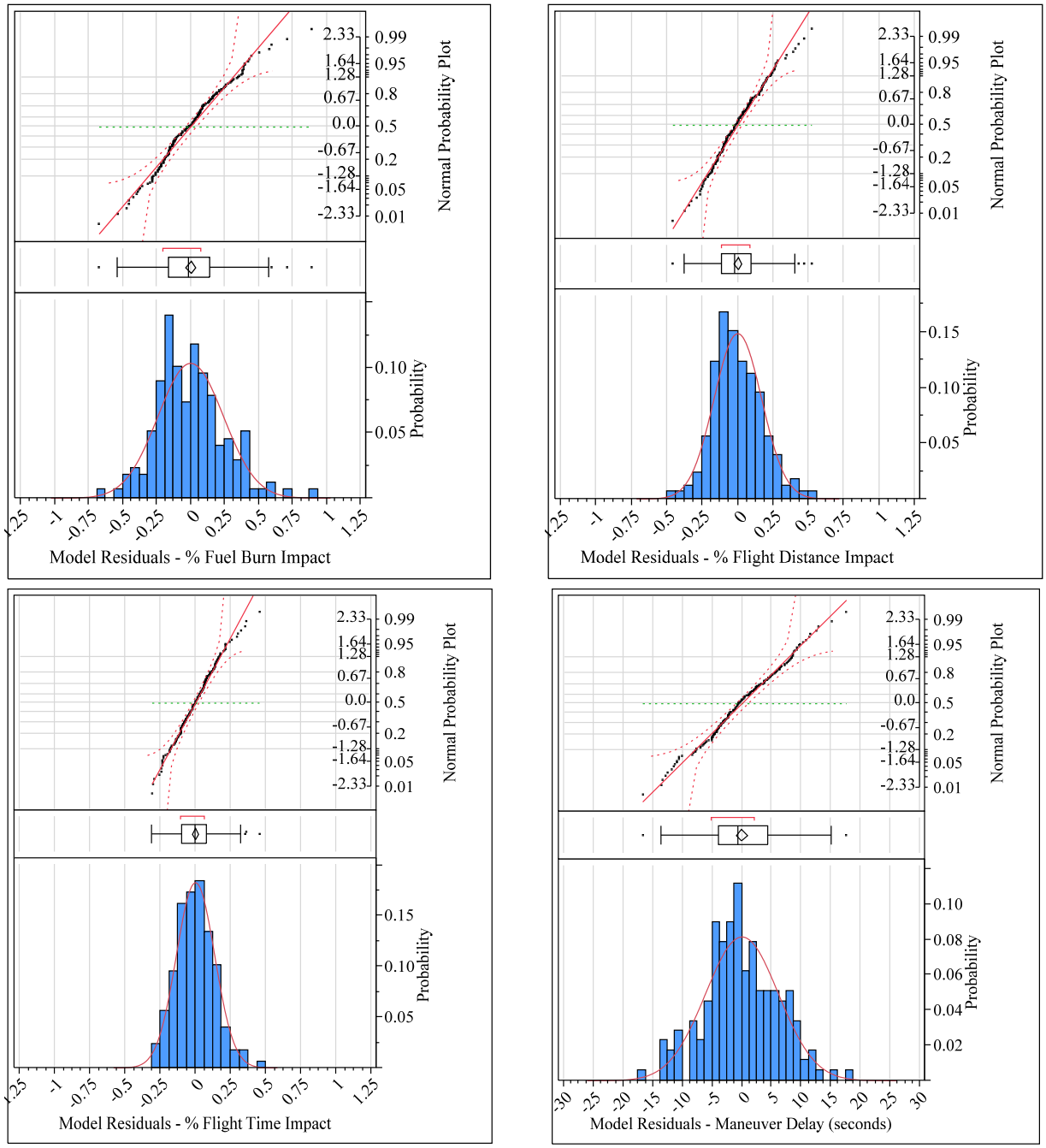


Figure 28: Residual Error Distributions for the Four Responses from Model 2

The model assumes that the unaccounted for variation or error in the model, referred to as random error, $\varepsilon_{n(ijkl)}$ in Eq. 2 is normally distributed. An additional validation of the model is to test the residuals for normality. These residual errors are presented in Figure 28 for each of the four response variables. Figure 28 provides histograms overlaid with fitted normal distribution density lines, box plots, and normal probability plots for each response variable. The histograms and box plots illustrate that the distributions are fairly symmetric and centered at zero as expected if normally distributed. The normal probability plot illustrates for each response that the model errors fall along the diagonal probability line, indicating that

each is at least approximately normally distributed. This provided further evidence that the model was indeed adequate.

Table 17 provides a summary of the Model 2 results on all four responses (p-values < 0.05 are statistically significant, < 0.10 marginally significant, and < 0.5 are of interest). The two main factor effects of action time and warning time are statistically significant for all four responses. The interaction effect of these two factors is statistically significant for all four responses and the squared (non-linear) effect of warning time is statistically significant as well, while the action time's squared effect is marginally significant only for the fuel burn response variable. Airspace region has mixed results. It has significance for percentage fuel burn and flight distance impact only. There are some interactions with the airspace region factor with other factors under some of the responses, especially with warning time. The year factor was not statistically significantly, nor was its interactions with other factors, but it did have some p-values as low as 0.13 indicating it is impacting the factors in some way even though below the threshold for statistical significance. The squared (non-linear) term for action time was only marginally significant for percentage fuel burn impact response only.

Table 17: Summary of Model 2 Effect Tests for Response Variables

Source	DF	%FB Impact P-Value	%FD Impact P-Value	%FT Impact P-Value	Maneuver Delay P-Value
Year	1	0.9120	0.3358	0.1404	0.1724
Airspace Region	2	<.0001*	0.0017*	0.8566	0.9133
Action Time	1	<.0001*	<.0001*	<.0001*	<.0001*
WarningTime	1	<.0001*	<.0001*	<.0001*	<.0001*
Year × Airspace Region	2	0.8260	0.6443	0.1826	0.1316
Year × Action Time	1	0.5508	0.2103	0.9344	0.8718
Year × Warning Time	1	0.9560	0.6869	0.4443	0.2181
Airspace Region × Action Time	2	0.2001	0.0182*	0.6983	0.2153
Airspace Region × WarningTime	2	<.0001*	0.0308*	0.8660	<.0001*
Action Time × Warning Time	1	<.0001*	0.0003*	0.0056*	0.0032*
Action Time × Action Time	1	0.0578	0.6440	0.5361	0.6849
WarningTime × Warning Time	1	<.0001*	<.0001*	<.0001*	<.0001*

Interactions play an important role in a multi-variable experiment. Table 17 provides the p-values for the interaction terms of the experiment as well as the main effects. As already highlighted, some response variables may have a p-value indicating the interaction is statistically significant, marginally significant, or just of interest with probability estimates less than 0.5. If an interaction effect is present, the effect of one variable will impact the effect of another simultaneously. Figure 29 illustrates this relationship graphically for the percentage fuel burn impact response variable. It plots the high and low levels for each factor as a function of the other factors, with the exception of the categorical factor airspace region which has three levels. Thus, for the interaction for the airspace region and warning time factors, the modeled response curves for each airspace region level do cross, indicating that there is an interaction effect between these two factors. This is consistent with the p-value of less than 0.0001. For the interaction of airspace region and action time, the p-value was 0.20, which is above marginal and not statistically significant yet indicating there may be a weak interaction occurring. Graphically, Figure 29 illustrates this weak interaction because the airspace regions of east and central seem parallel but the west does exhibit a different slope without actually crossing for the duration of the experiment.

In the same manner as the % fuel burn impact, Figure 30 illustrates the interaction profile for maneuver delay. One example from Table 17 is the airspace region factor which is not statistically significant alone.

However, the p-value of the two-way interaction between airspace region and warning time is statistically significant. Figure 30 illustrates this interaction as well, where all three airspace region curves cross in the box aligned under the warning time factor.

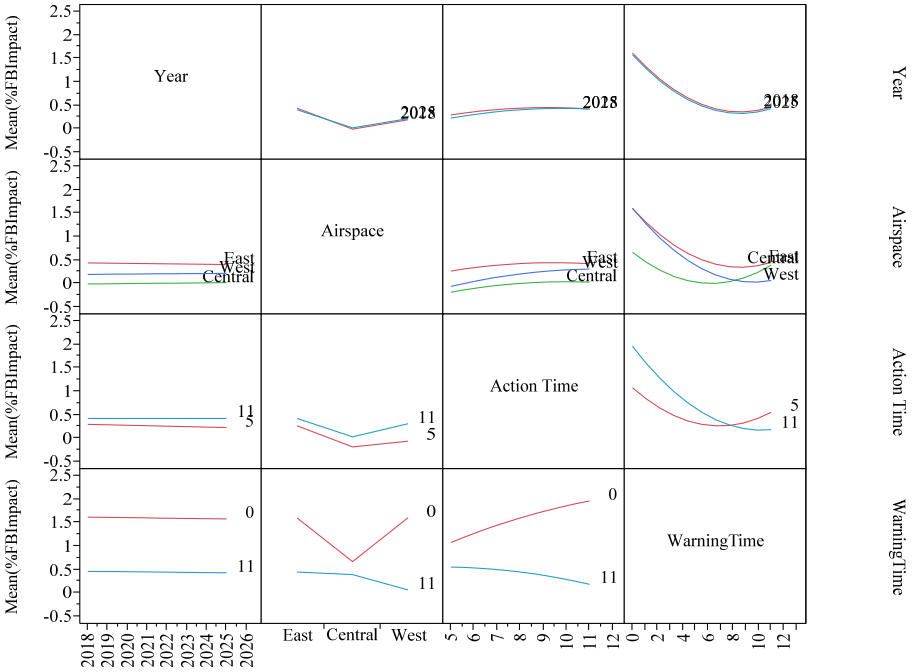


Figure 29: Interaction Profile for % Fuel Burn Impact Response Variable

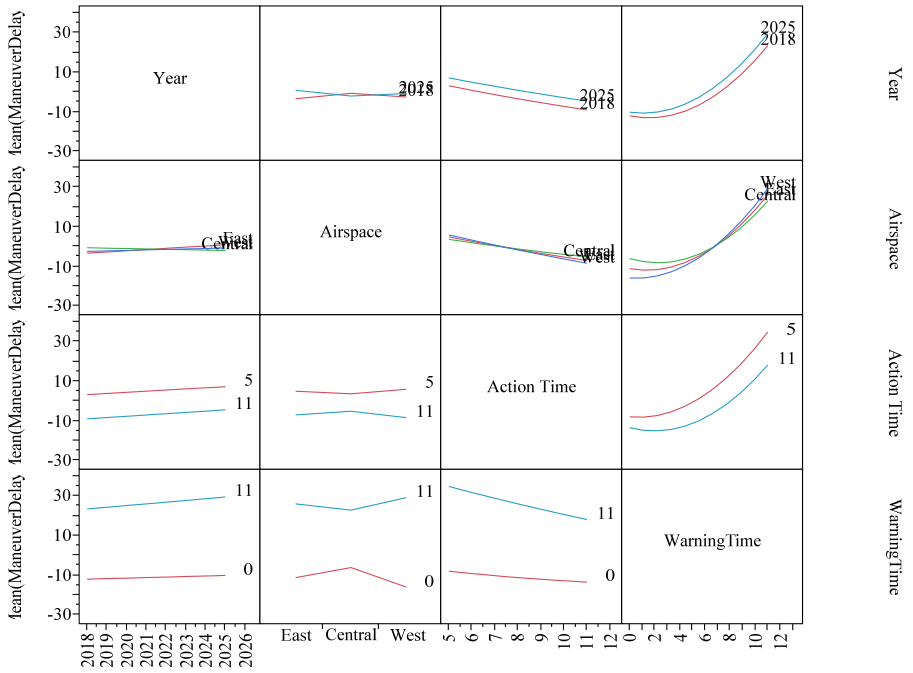


Figure 30: Interaction Profile for Maneuver Delay Response Variable

The model defined in Eq. 2 requires the estimate of coefficients or parameters for each factor and level if fixed (airspace region) or for each factor if continuous (year, action time, and warning time). The Model 2 results presented previously are based on the fit parameters listed in Table 19. Even though all the parameters are included from Eq. 2 the p-value is provided for each factor, which is the significance level of the t-test of the parameter estimate. The p-value is provided as a guide on the statistical significance of that particular factor level's coefficient. The actual model from Eq. 2 is expanded in Table 18 with the coefficients from Table 19 (labeled *code*). The model is the addition of three sets of terms, including the intercept and main effects (single terms), the two-way interaction terms, and the squared non-linear terms. The fixed airspace region effect has coefficients defined per level and are selected on a discrete basis, while the continuous terms are simply functions of the particular factor level. The two-way interactions and squared terms have offsets built into the formula (e.g. AT_k *-8*). The synthesis of this model and discussion of the resulting parameters will be presented in the next section.

Table 18: Expansion of Model 2 Equation

Intercept & Main Effects:	$A0 + A1 \times Y_i + (A_j$=east, $A2e$ or A_j=central, $A2c$ or A_j= west, $A2w) + A3 \times AT_k + A4 \times WT_l$
Two-way Interactions:	$(Y_i - 2021) \times (A_j$=east, $A5e$ or A_j=central, $A5c$ or A_j= west, $A5w) +$ $A6 \times (Y_i - 2021) \times (AT_k - 8) +$ $A7 \times (Y_i - 2021) \times (WT_l - 6.4) +$ $(A_j$=east, $A8e$ or A_j=central, $A8c$ or A_j= west, $A8w) \times (WT_l - 6.4) +$ $(A_j$=east, $A9e$ or A_j=central, $A9c$ or A_j= west, $A9w) \times (AT_k - 8) +$ $A10 \times (AT_k - 8) \times (WT_l - 6.4)$
Squared Terms:	$A11 \times (AT_k - 8)^2 +$ $A12 \times (WT_l - 6.4)^2$

Table 19: Model 2 Parameter Estimates for Response Variables

Code	Term	% FB Impact		% FD Impact		% FT Impact		Maneuver Delay (s)	
		Estimate	P-Value	Estimate	P-Value	Estimate	P-Value	Estimate	P-Value
A0	Intercept	-1.171497	0.9279	-8.730367	0.3338	-10.90746	0.1381	-462.2571	0.1612
A1	Year	0.0007079	0.9120	0.0043012	0.3358	0.0053645	0.1404	0.2227189	0.1724
A2e	Airspace Region [East]	0.2150073	<.0001*	0.06733	0.0004*	0.0047062	0.7553	-0.04267	0.9498
A2c	Airspace Region [Central]	-0.208422	<.0001*	-0.038404	0.0400*	-0.008369	0.5796	0.268275	0.6922
A2w	Airspace Region [West]	-0.006585	0.8050	-0.028926	0.1209	0.0036632	0.8083	-0.225605	0.7392
A3	Action Time	0.0411354	<.0001*	-0.032629	<.0001*	-0.032755	<.0001*	-1.955598	<.0001*
A4	WarningTime	-0.059318	<.0001*	0.0714181	<.0001*	0.0547832	<.0001*	4.1111072	<.0001*
A5e	(Year-2021) × Airspace Region [East]	-0.005576	0.5385	-0.005308	0.4008	0.0070412	0.1710	0.3886841	0.0927
A5c	(Year-2021) × Airspace Region [Central]	0.0032108	0.7231	0.0049158	0.4365	-0.009035	0.0796	-0.416582	0.0717
A5w	(Year-2021) × Airspace Region [West]	0.0023655	0.7941	0.0003927	0.9504	0.0019933	0.6976	0.0278983	0.9035
A6	(Year-2021) × (Action Time-8)	0.0017102	0.5508	0.0025062	0.2103	0.0001335	0.9344	0.0117496	0.8718
A7	(Year-2021) × (Warning Time-6.4)	9.3636e-5	0.9560	0.0004768	0.6869	0.0007358	0.4443	0.0532466	0.2181
A8e	Airspace Region [East] × (Action Time-8)	-0.015233	0.2027	-0.021837	0.0093*	-0.004705	0.4862	-0.044927	0.8821
A8c	Airspace Region [Central] × (Action Time-8)	-0.00549	0.6455	0.0190712	0.0228*	0.0051703	0.4443	0.482224	0.1129
A8w	Airspace Region [West] × (Action Time-8)	0.0207234	0.0838	0.0027658	0.7393	-0.000465	0.9451	-0.437297	0.1503
A9e	Airspace Region [East] × (Warning Time-6.4)	-0.014674	0.0392*	0.0130444	0.0088*	0.0021104	0.5981	0.0103207	0.9542
A9c	Airspace Region [Central] × (Warning Time-6.4)	0.064985	<.0001*	-0.005382	0.2752	-0.000729	0.8554	-0.737876	<.0001*
A9w	Airspace Region [West] × (Warning Time-6.4)	-0.050311	<.0001*	-0.007662	0.1210	-0.001381	0.7300	0.727555	<.0001*
A10	(Action Time-8) × (Warning Time-6.4)	-0.019003	<.0001*	-0.005703	0.0003*	-0.003547	0.0056*	-0.169747	0.0032*
A11	(Action Time-8) × (Action Time-8)	-0.008998	0.0578	-0.001518	0.6440	0.0016523	0.5361	0.048627	0.6849
A12	(WarningTime-6.4) × (Warning Time-6.4)	0.0171429	<.0001*	0.0093719	<.0001*	0.0045157	<.0001*	0.4072505	<.0001*

3.2.2.2.3 Synthesize Results

The experimental results produce a statistical model defined in Table 18 with coefficient estimates listed in Table 19. It is this model that allows us to draw conclusions on the relationships and net effects of the various factors under study. The JMP® commercial software tool provides an interactive model calculator called the predictor profiler that allows us to examine the effects of the various factors of the model[10]. The following Figure 31 and Figure 32 illustrate the predictor profile plots for the airspace region at its central level at 11 and 0 minutes warning time, respectively. The slopes of the plotted lines indicate the magnitude and direction of each factor's effect on the model. The curvature in the action time and warning time factors indicate their non-linear effects. The y-axis plots the response variable estimates from the model and the decimal numbers on each y-axis represents the modeled response variable at the levels specified in the figures. Thus, for airspace region central at 11-minute warning time, the % fuel burn impact is 0.376 and at 0 minutes warning time it is modeled at 0.656, while the year set to 2018 and 8-minute action time. At high warning times, the % fuel burn impact curve decreases as a function of action time from 0.47 to 0.12. For lower warning times, the % fuel burn impact curve is quite different and rises as a function of action from 0.119 to 1.03. Thus, it is not just the main effects but the two-way interaction and non-linear effects impacting the results. The action time is the maximum amount of time before loss of separation that the simulation of a conflict resolution will act on a predicted conflict. It does not preclude from acting on a conflict sooner if needed (e.g. a near term conflict pop's up and needs to be addressed immediately where warning time is less than action time). Also, there are a number of conflicts that are excluded from the action time restriction. This occurs if the predicted conflict start time is within 20 minutes of the metering fix of the flight. If so, the flight will be resolved at the full warning time and not wait until the action time. Therefore, if there exists sufficient warning time beyond eight minutes there seems to be a reduction by acting more strategically with higher action times in the % fuel burn impact, where on average it reduces to a low of 0.12%. If the warning time is much less at the five minutes level for example, the % fuel burn impact does not improve for higher action time but increases to as high as 1%. Similar results are exhibited for the other two airspace regions. In Figure 33 and Figure 34, the results are illustrated for the airspace region east, and the Figure 35 and Figure 36 illustrates the same for airspace region west.

For the maneuver delay response variable, the performance is much more linear for action time unlike the fuel burn response but is non-linear for warning time like the fuel burn. maneuver delay is decreasing as a function of action time for all warning times but is not invariant to the warning time curve. At high warning time, the maneuver delay is reduced from 30 seconds to 16 seconds on average as it moves from low to high action times. For the low warning time, the maneuver delay is reduced from -3 seconds to -5 seconds on average. In other words, for high warning time the net effect is higher delay overall but by acting sooner through higher action times there is significant reduction in maneuver delay time on average by approximately 14 seconds per maneuver. If there is a low warning time event, the overall net delay is much lower (negative means less than base line even), but the more importantly the savings in delay for acting more strategically is less only about 2 seconds on average. These results are consistent for the other airspace region levels (west and east) as illustrated in Figure 33 to Figure 36.

10 For details on the JMP® software tool and the predictor profiler see www.jmp.com.

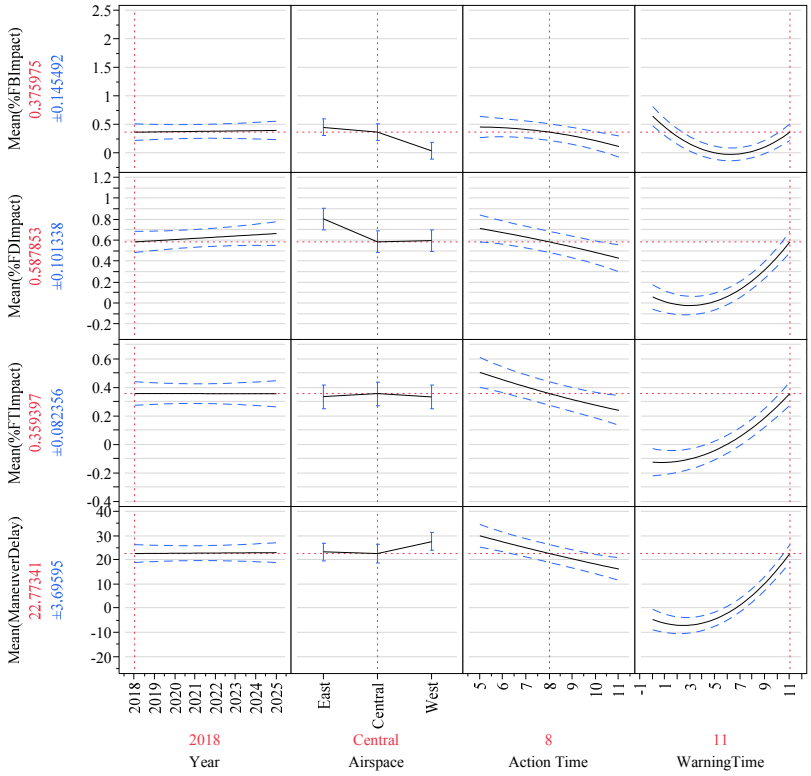


Figure 31: Predictor Profiler for Airspace Region-Central and Warning Time-11 Minutes

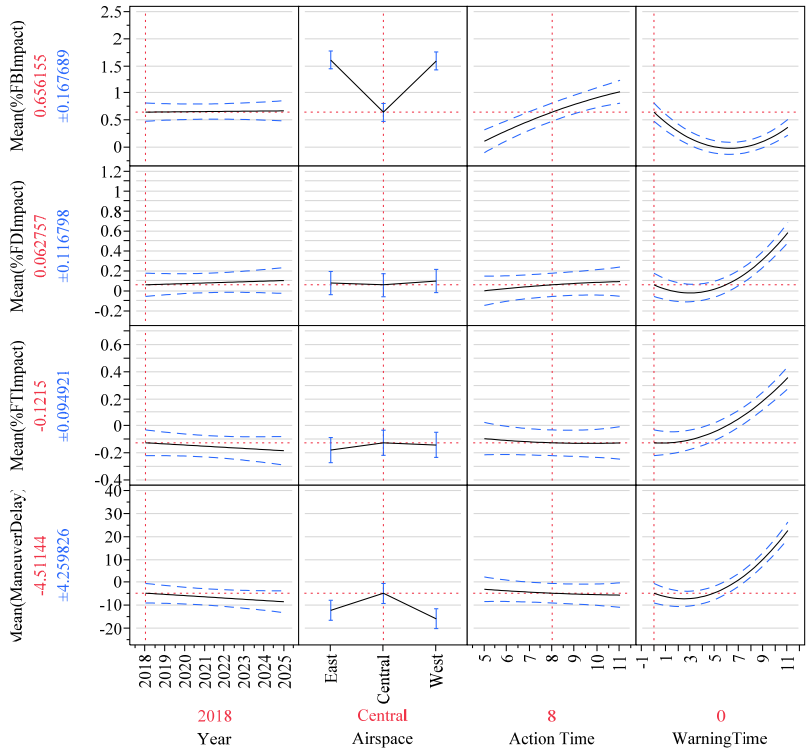


Figure 32: Predictor Profiler for Airspace Region-Central and Warning Time-0 Minutes

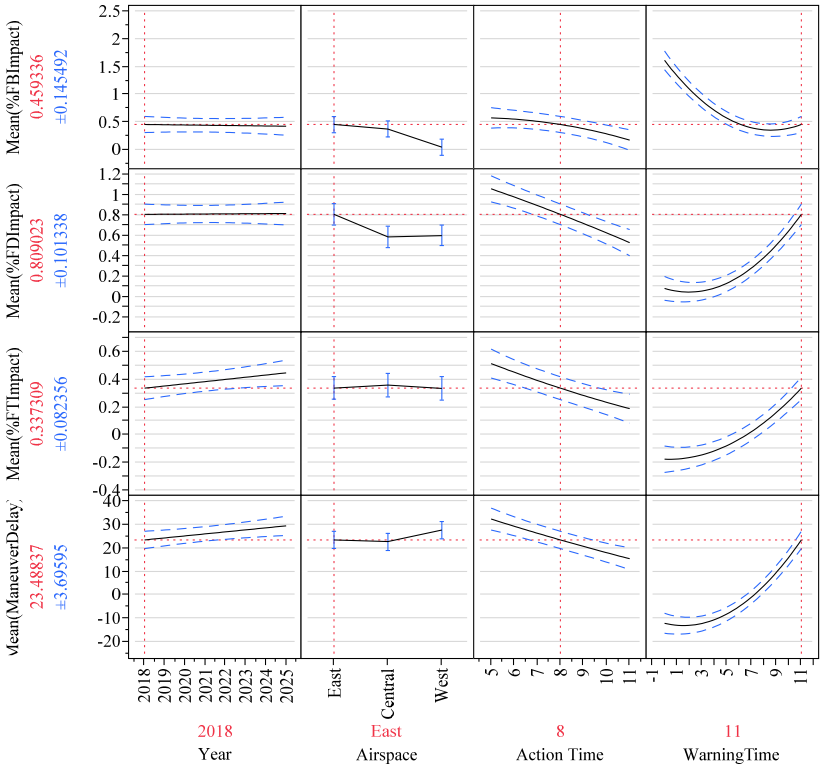


Figure 33: Predictor Profiler for Airspace Region-East and Warning Time-11 Minutes

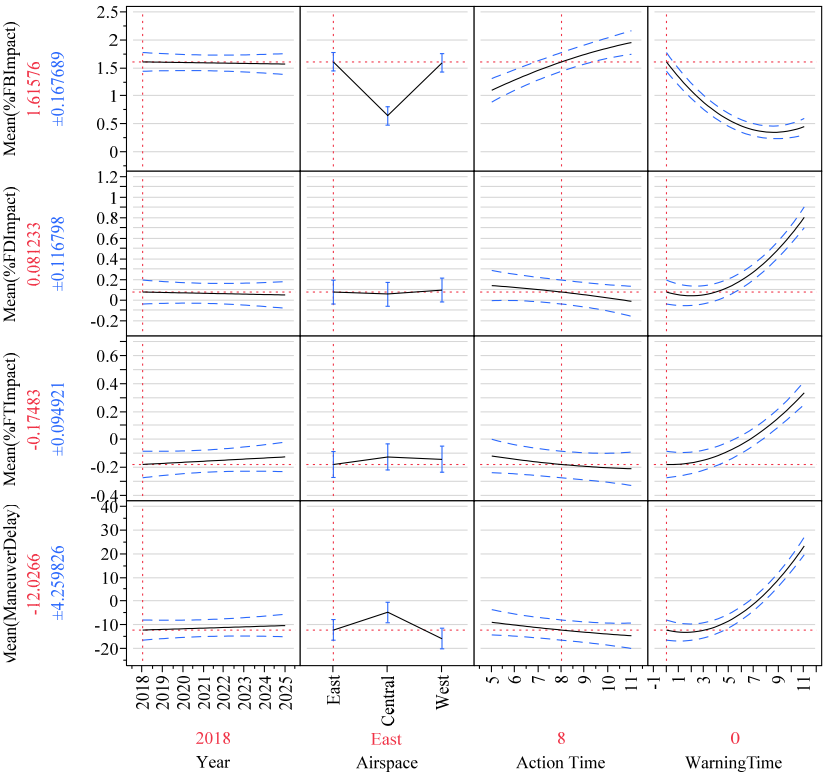


Figure 34: Predictor Profiler for Airspace Region-East and Warning Time-0 Minutes

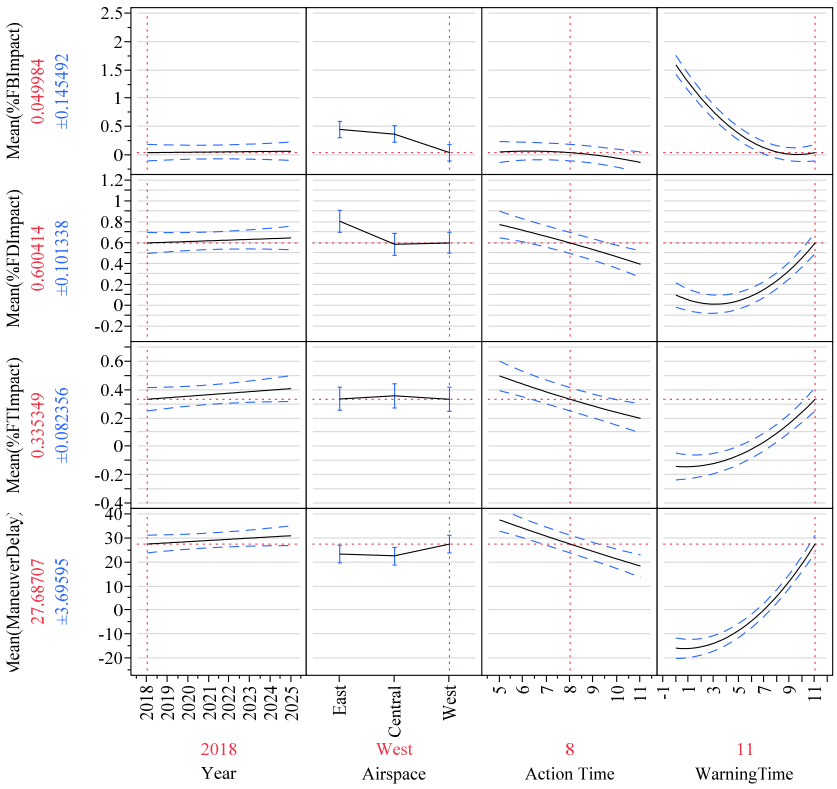


Figure 35: Predictor Profiler for Airspace Region-West and Warning Time-11 Minutes

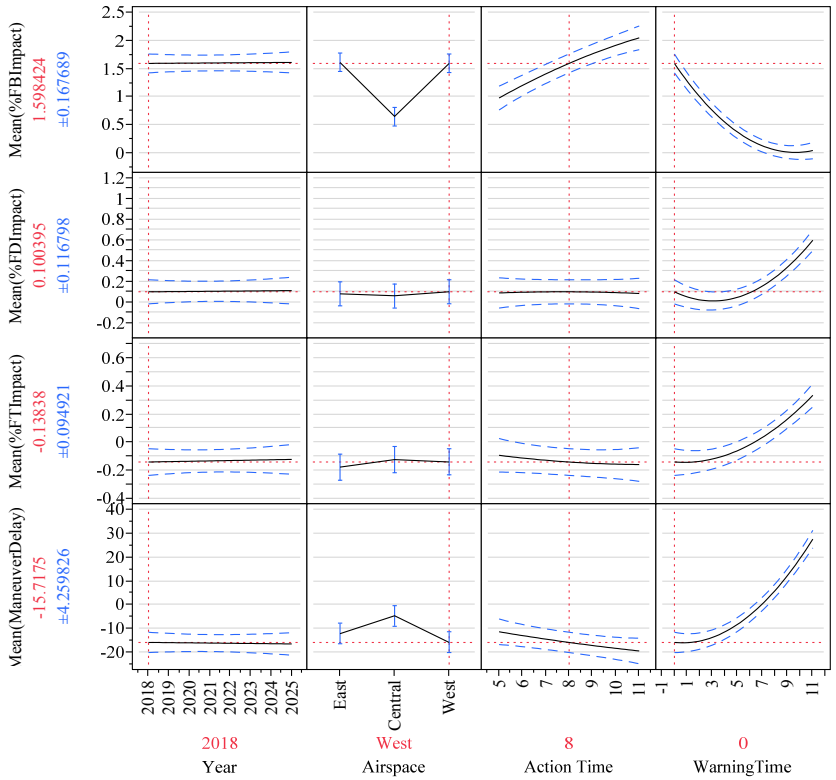


Figure 36: Predictor Profiler for Airspace Region-West and Warning Time-0 Minutes

The other response variables including percentage of flight distance and flight time impacts have for the most part continuously descending functions as a function of action time. Like maneuver delay, this is not to say the impact of action time on these response variables is invariant to warning time, because it is not. For the airspace region east, if a low warning time is modeled the % flight delay impact and % flight time impact reduces about 0.15% and 0.1%, respectively. This is contrasted with the modeled results at the high warning time where % flight delay reduces approximately 0.5% and % flight time reduces approximately 0.3%.

In summary, the results require some interpretation and are multivariate in nature because of the strong interaction of action time and warning time in particular along with squared terms of these same factors. Overall there are statistically significant effects as action time increases, yet small in magnitude, and contingent on the fixed airspace region levels and interaction of warning time. The soundness of the model is supported by the R^2 and residual analysis. The next section will provide additional validation and insights of the soundness of the modeled results by examining specific flight examples.

3.2.2.2.4 Additional Experimental Model

One of the more subtle findings of experimental Model 2 defined in the previous Section 3.2.2.2.2 is the significant non-linearity of the warning time factor on all the response variables. This can be attributed to several causes but one possible reason is another factor not accounted for in the model. In Section 3.2.1.2, conflict resolution properties were described and included a description of four conflict resolution maneuver types: horizontal, direct-to, vertical, and speed. The horizontal maneuver type simulates the lateral heading vector of air traffic control. This occurs when an air traffic controller directs an aircraft to change course temporarily in a straight path off the cleared flight plan and then at some time in the future the aircraft is cleared to return to the original flight plan route. This is illustrated in the top left corner of Figure 37, which illustrates all four maneuver types. The direct-to maneuver consists of a clearance to a downstream fix. The vertical maneuver typically includes a temporary altitude maneuver of a cruising aircraft as illustrated in Figure 37 or a temporary level off during a climb or descent. Finally, the speed maneuver consists of a purposeful change in the aircraft's speed to generate an longitudinal separation with the other aircraft. If the experiment was rerun, it would require four times the quantity of treatment runs as specified in Table 4 (180 x 4 = 720 runs). Thus, a more expeditious approach was used to examine the impact this new factor had on the response variables.

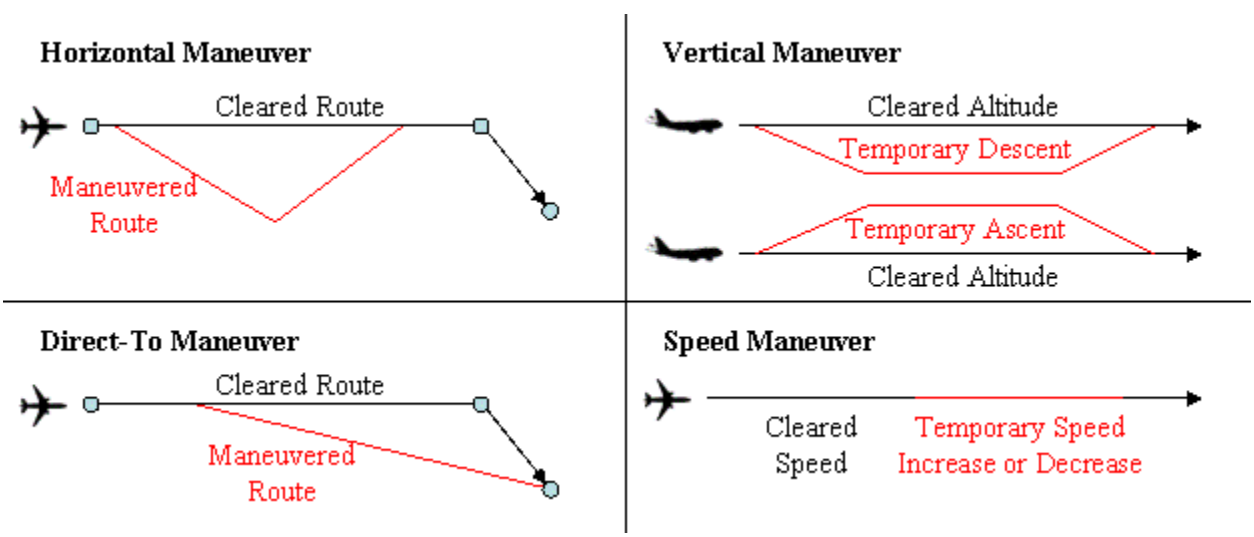


Figure 37: Conflict Resolution Maneuver Type Diagrams

The relatively weak year factor as reported in Table 17 had a statistically insignificant effect on the four response variables. Therefore, for this additional Model 3, the year factor is removed and maneuver is inserted producing the following Eq. 3. Now with four levels for the maneuver factor the total number of treatments becomes 240 runs. However, there were only 235 treatment runs available resulting from five less runs available for high warning times of direct-to maneuvers.

Response:

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

Where:

M_i = maneuver type, i = 1, 2, 3,4
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*

The Eq. 3's Model 3 resulted in the following Figure 38, where all four response variables had excellent modeling error with R-squared (RSq) statistics ranging from 0.80 to 0.95. The plots illustrate the modeled response versus the measured value.

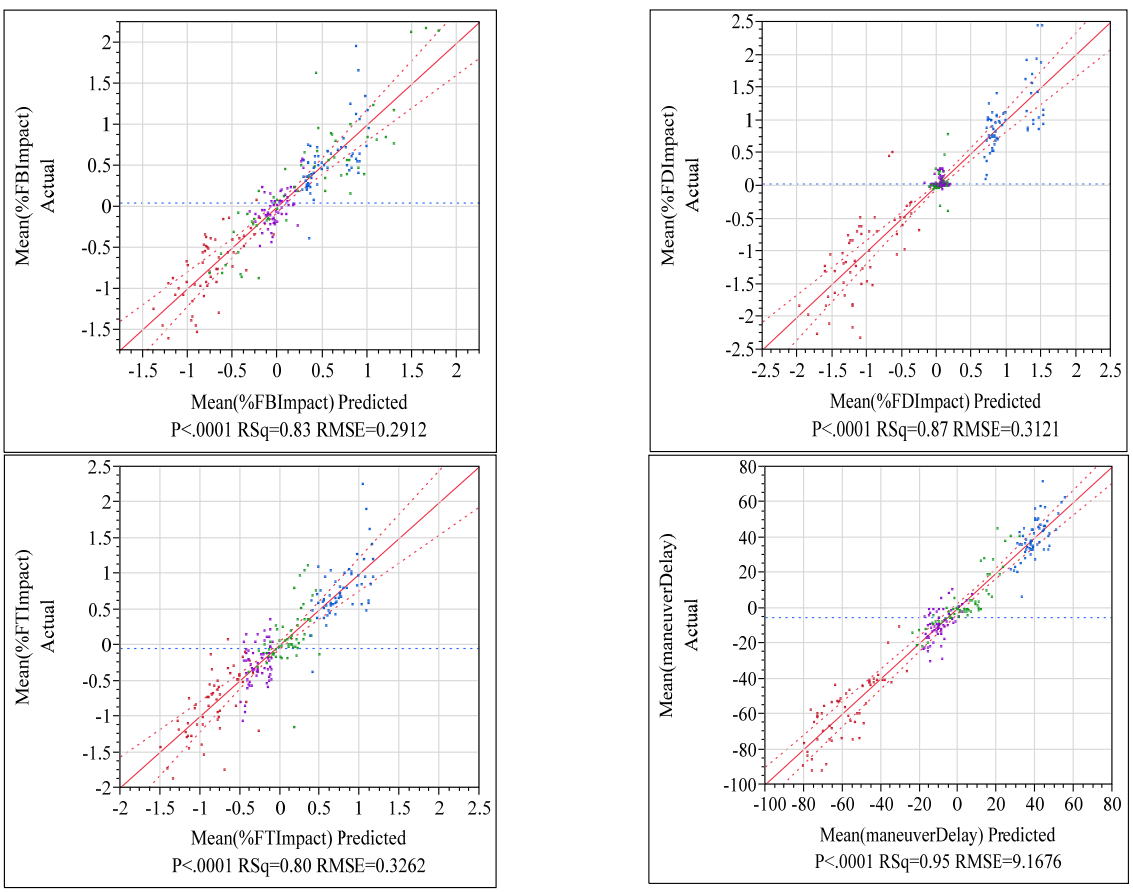


Figure 38: Full Factorial Leverage Plots per Response Result for Model 3

Another feature of the Figure 38 plots is the color code of the four maneuver types. The various maneuver types do tend to cluster, indicating their significance as an influential factor. The overall frequency of all conflict's resolution types was presented in Section 3.2.1.2 in Figure 22. This is a bit different than the frequency count of the single maneuver conflicts above FL 180 used for the experiment as illustrated in the following Figure 39. Vertical maneuvers dominate at 56%, with direct-to maneuvers at 19%, horizontal maneuvers at 15%, and speed at 10%. The difference between the overall conflict frequencies (i.e. all conflicts including all altitudes and multi-maneuver conflicts) and the single maneuver en route conflicts used in the experiment is attributed mostly to the lower altitude conflicts that had much higher speed maneuvers (52%) and horizontal (37%). More importantly, the vertical maneuver performance would tend to dominate the experimental results in the previous Model 2 when maneuver type was not accounted for. This further justifies including maneuver in the model as examined in Model 3.

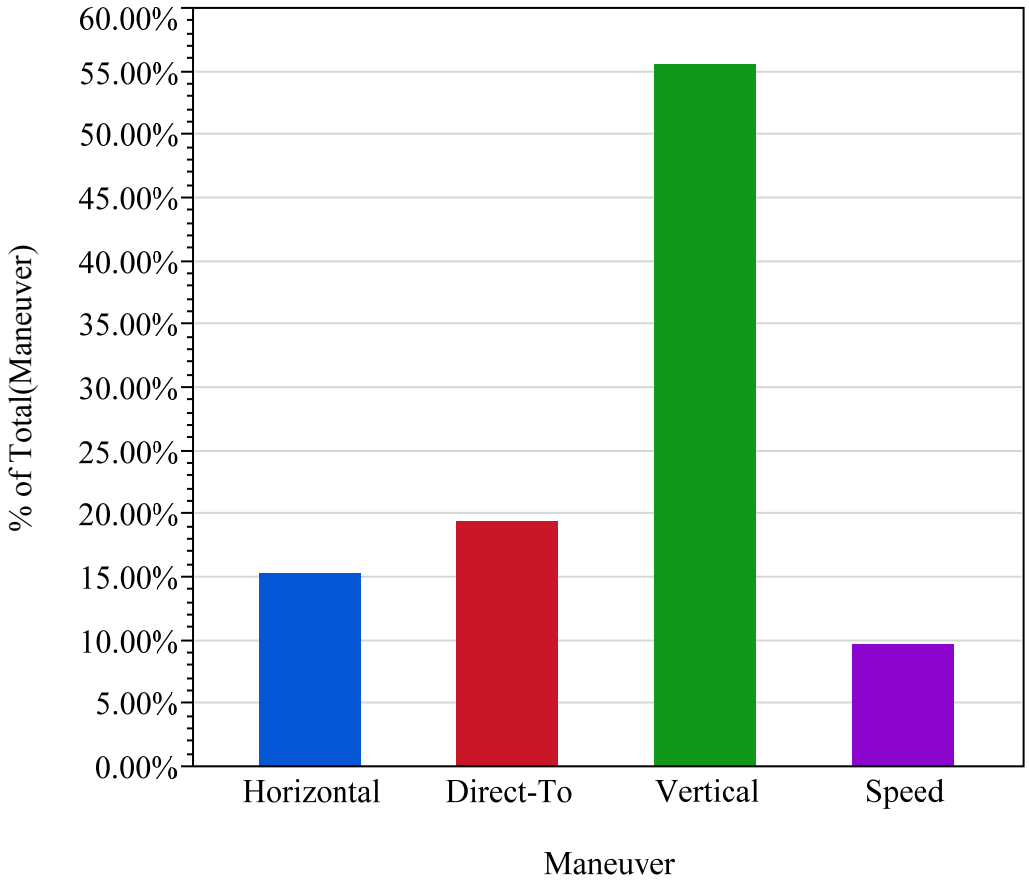


Figure 39: Overall Maneuver Frequencies from Model 3

Model 3's effect tests are listed in Table 20. With the exception of percentage of Flight time impact, all the responses have statically significant effects for airspace and maneuver factors. For percentage fuel burn impact (%FB impact), maneuver factor has significant interaction effects with all the other factors. However, the square terms of action time and warning time were insignificant for all four responses, indicating these factors are linear when taking into account the maneuver factor and its interactions. This was quite different than Model 2, where warning time was quite non-linear, and thus this non-linearity can be attributed to influence of the maneuver factor. The interaction of action time and warning time unlike Model 2 was not significant across all responses. Only for maneuver delay was the interaction significant and most notably had a marginal p-value for fuel burn impact at 0.2. Thus, the interaction of

maneuver on both action time and warning time may have added to the interaction between action time and warning time in Model 2, while in Model 3 it is segregated by maneuver resulting in less of an influential effect. Only maneuver delay exhibits a strong interaction effect between action time and warning time factors.

Table 20: Summary of Model 3 Effect Tests for Response Variables

Source	DF	%FB Impact P-Value	%FD Impact P-Value	%FT Impact P-Value	Maneuver Delay P-Value
Airspace	2	<.0001*	0.0065*	0.9977	<.0001*
Maneuver	3	<.0001*	<.0001*	<.0001*	<.0001*
Action Time	1	0.0305*	0.2263	0.0174*	<.0001*
WarningTime	1	0.1547	0.1244	0.0524	<.0001*
Airspace × Maneuver	6	<.0001*	<.0001*	<.0001*	<.0001*
Airspace × Action Time	2	0.0802	0.0613	0.3054	0.9692
Airspace × WarningTime	2	0.1043	0.3116	0.7396	0.0004*
Maneuver × Action Time	3	<.0001*	0.6836	0.2651	0.0021*
Maneuver × WarningTime	3	<.0001*	<.0001*	<.0001*	<.0001*
Action Time × WarningTime	1	0.2079	0.9868	0.2717	0.0417*
Action Time × Action Time	1	0.5653	0.8505	0.7890	0.7481
WarningTime × WarningTime	1	0.3679	0.5750	0.6128	0.5837

Appendix C in Section 9 of the report provides the detailed map of Model 3's Eq. 3 and listing of all the fitted coefficients for each response variable's model. It also includes histograms of the model residuals for all four response variables, illustrated in Figure 62.

The following Figure 40 through Figure 43 provide the four predictor profile plots of the model results for each maneuver type, horizontal, direct-to, vertical, and speed, respectively. It is fixed at central and 11 warning time for airspace and warning time factors. The general trend for horizontal maneuvers is action time has a negligible or flat effect on the three % impact responses and a slightly reducing effect on maneuver delay. The general trend for speed maneuvers follows the same pattern. However, vertical maneuvers have a different effect. For these maneuvers, the % fuel burn impact and % flight delay impact both increase as a function of action time, while maneuver delay and % flight time impact decreases significantly. For direct-to maneuvers, all the responses are reduced as a function of action time, indicating for these maneuvers a savings is occurring across the board as a function of action time.

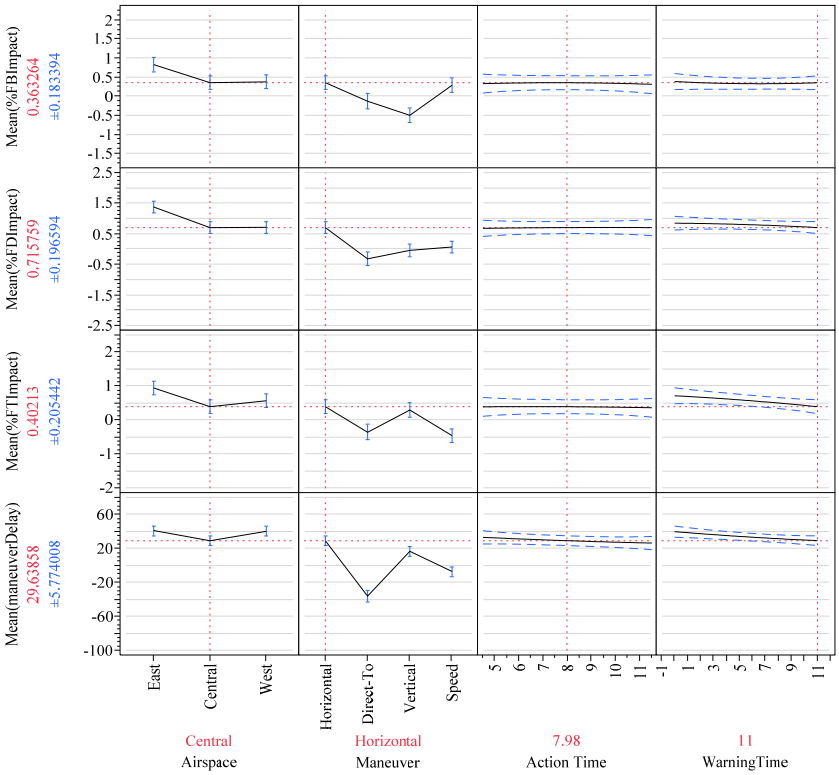


Figure 40: Predictor Profiler for Maneuver-Horizontal and Warning Time-11 Minutes

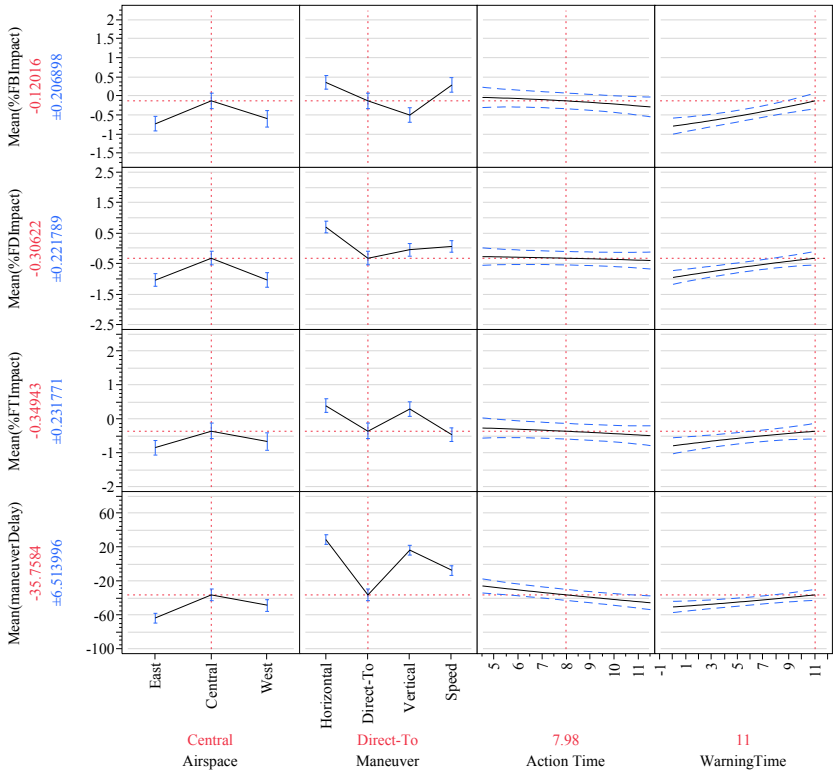


Figure 41: Predictor Profiler for Maneuver-Direct-to and Warning Time-11 Minutes

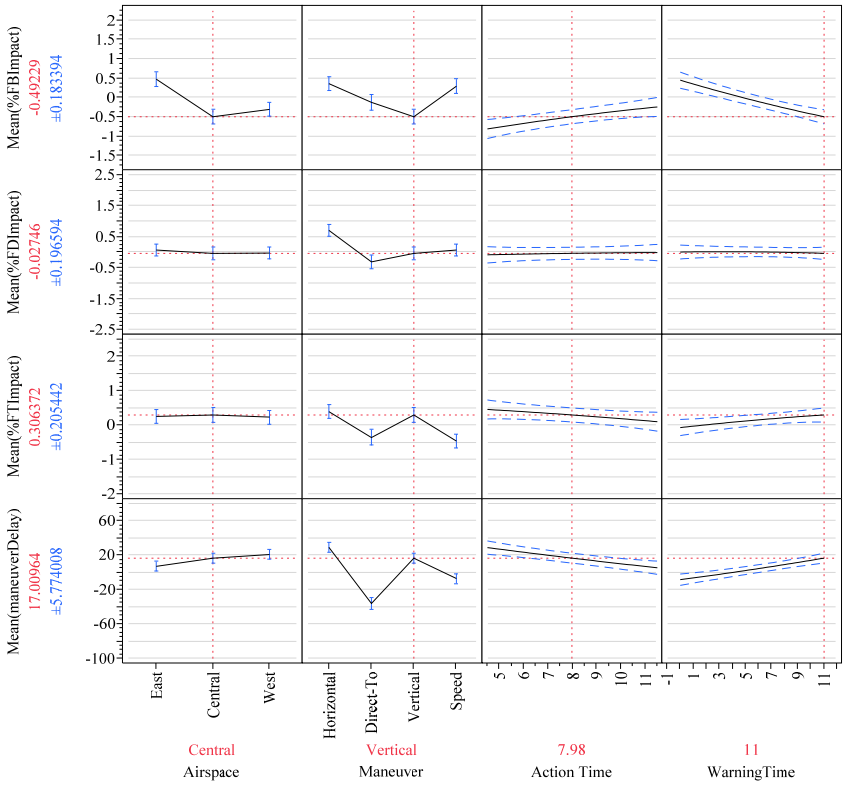


Figure 42: Predictor Profiler for Maneuver-Vertical and Warning Time-11 Minutes

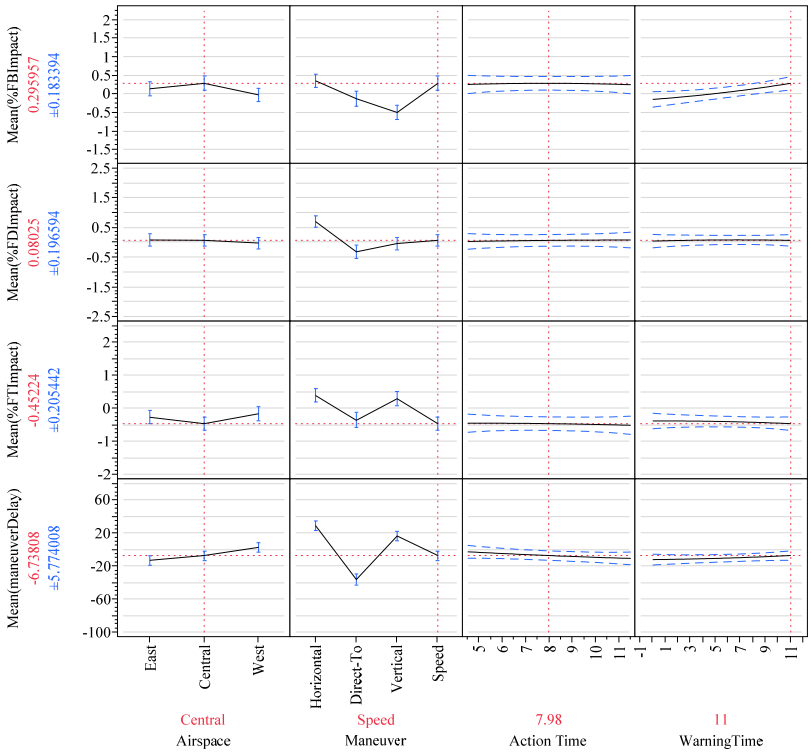


Figure 43: Predictor Profiler for Maneuver-Speed and Warning Time-11 Minutes

3.2.3 Flight Examples

This section presents eight example conflicts that were selected to demonstrate how the resolution maneuvers implemented by the simulation logic vary with action time. The examples also illustrate some of the idiosyncrasies within ACES that may or may not be representative of the operational system. Each example addresses an individual conflict and presents relevant information and conflict statistics. The paths of the two flights involved are depicted from the nominal baseline scenario and also from the four action time scenarios to show the effect of action time on the resolution maneuver. Conflicts are characterized by the two aircraft involved and the anticipated time of first loss. In selecting conflicts for these examples, only events with the same detection time and maneuvered flight for all action time scenarios in a given year and airspace region are considered.

Table 21 gives an overview of the flight examples examined in this section. The examples attempt to capture a wide array of conflicts with all of the resolution options, a large range of detection times, and sampling of the ACES model's behavior. All of the examples report the expected benefit in delay, a trend that should be expected since ACES chooses resolution maneuvers based on which maneuver results in the minimum added delay. Overall, these examples are a way to validate the model as well as give insight into the process ACES uses to resolve a conflict with different action time parameters.

Table 21: Flight Example Overview[11]

Example Section	Maneuver	Detection Time	FB Trend	Delay Trend	Main Point of Example
3.2.3.1	Horizontal (5 min.) Direct-To (7, 9, 11 min)	16:05	Benefit	Benefit	Illustrates benefit in both fuel and delay response variables
3.2.3.2	Vertical (5 min) Direct-To (7, 9, 11 min)	11:15	Benefit	Benefit	Illustrates benefit in both fuel and delay response variables
3.2.3.3	Direct-To (all scenarios)	12:40	Benefit	Benefit	Illustrates benefit in both fuel and delay response variables
3.2.3.4	Horizontal (all scenarios)	19:35	Benefit	Benefit	Illustrates benefits when using all horizontal maneuvers
3.2.3.5	Horizontal (all scenarios)	1:10	Inconclusive	Benefit	Illustrates pop-up conflict; stochastic result in ACES may prevent using same maneuver in all scenarios
3.2.3.6	Vertical (all scenarios)	13:05	No Benefit	Benefit	Illustrates ACES waiting until flight is at highest FL possible before maneuvering; flight switching from CAS to Mach during level-off; level-off time equals action time parameter
3.2.3.7	Vertical (all scenarios)	6:05	No Benefit	Benefit	Illustrates flight switching from CAS to Mach during level-off; level-off time equals action time parameter
3.2.3.8	Speed (all scenarios)	14:40	Inconclusive	Benefit	Illustrates example of a speed resolution

11 For the "FB Trend" and "Delay Trend" columns, "Benefit" denotes a benefit as a function of increased action time (i.e. both fuel consumption and delay decrease with an increasing warning time), "No Benefit" denotes the opposite of the expected benefit (i.e. both fuel consumption and delay increase with an increasing warning time), and "Inconclusive" denotes no noticeable trend illustrated in the examples.

3.2.3.1 Example 1

The first example documents a conflict that occurs in the central 2018 scenarios. The maneuvered flight is taking off from O'Hare International Airport (KORD) going south while the other flight is coming from Denver and landing at Indianapolis International Airport (KIND). Both aircraft are Canadair Regional Jets, CRJ-700. When the two flights approach each other and come into conflict, the maneuvered flight is climbing towards its assigned altitude of FL360 and the other is cruising at altitude FL350. Horizontal flight tracks of both flights are depicted in Figure 1, where the maneuvered flight is designated as Flight 1 and the other as Flight 2.

The conflict is detected 16 minutes and five seconds before the anticipated time of first loss. The location of the two aircraft at this detection time is indicated in Fig.1 as "Flights Warned of Impending Conflict." The time period during which the flights would have experienced a loss of separation is 25 seconds and the encounter angle is 135.1°. The conflict altitudes are 35,785 feet for Flight 1 and 35,000 feet for Flight 2, with horizontal separation of 4.88 nautical miles.

Table 22 presents relevant information for this conflict compared across the four different action time scenarios. With increasing action times the number of maneuver options that could potentially resolve the conflict are non-decreasing, so there are at least as many or more options when more strategic action times are employed. This corresponds with the availability of more optimal maneuvers.

From Table 22 it is observed that in the 7-, 9-, and 11-minute action time scenarios a direct-to resolution maneuver was implemented, with maneuver delay and additional fuel consumption decreasing with larger action times (representing a more strategic approach), while in the 5-minute action time scenario a horizontal vector maneuver was used, with a larger associated maneuver delay. The direct-to maneuver in this case is more fuel and time efficient and is available in scenarios using more strategic, larger action times

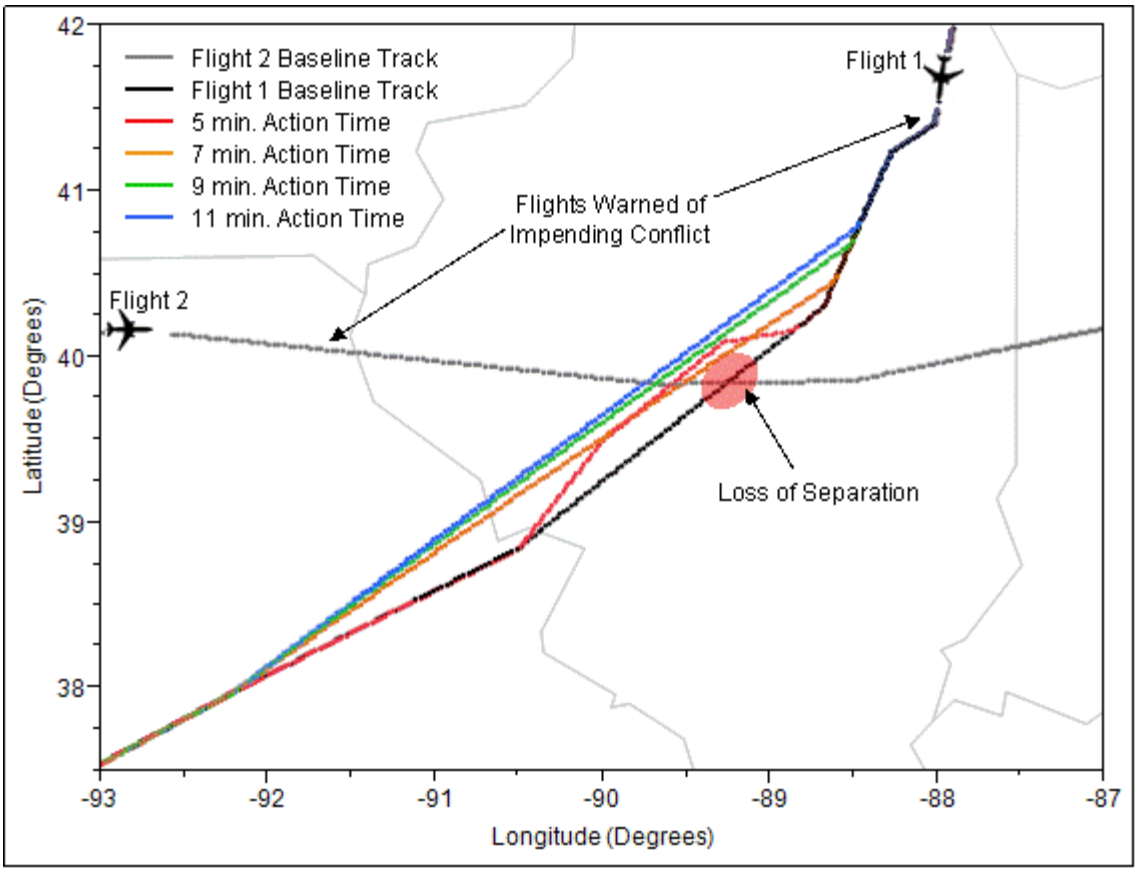


Figure 44: Example 1 - Horizontal Flight Tracks

Table 22: Example 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	Std. Horizontal	7	3	28.87	34
7	Direct-To	8	6	-26.15	-26
9	Direct-To	8	8	-34.62	-42
11	Direct-To	8	9	-41.73	-48

3.2.3.2 Example 2

This example is from the west region at the 2020 traffic level. Figure 45 shows the flight paths of the two conflicting flights in the horizontal domain. Figure 46 shows the flight paths in the vertical domain. Flight 1 is an Airbus A320 that is taking off from Reno-Tahoe International Airport (KRNO) heading west to Denver International Airport (KDEN). Flight 2 is also an Airbus A320 that is en route from Oakland International Airport (KOAK) to John F. Kennedy International Airport (KJFK) in New York City. The conflict occurs as Flight 1 is ascending to its assigned cruising altitude and, consequently, is maneuvered to avoid losing minimum separation with Flight 2.

As seen in Figure 45, they approach each other with an encounter angle of 1.1° (making it an in-trail encounter) and the conflict occurs when Flight 1 reaches an altitude of 32,000 feet. As the figure shows, only three of the scenarios use a horizontal maneuver to resolve the conflict. As shown in Table 23, the resolution used in the 5-minute action time scenario is a vertical resolution while the remaining three scenarios shown in Figure 45 use a direct-to maneuver. The flights are warned about the conflict 675 seconds before the loss of separation, so the maneuver can start as soon as Flight 1 reaches the action time parameter in all four scenarios.

The effect of the changing action time can be observed clearly in Figure 45. Flight 1 in the 11-minute scenario (blue trajectory) is maneuvered earlier than it is in the 9-minute scenario (green trajectory) followed by the 7-minute scenario (orange trajectory). The maneuver for the 5-minute scenario, displayed in Figure 46 follows this trend as well. As the figure shows, Flight 2 is at its cruising altitude of 33,000 feet when Flight 1, attempting to climb to 37,000 feet, approaches it. A significant difference for this maneuver, other than the obvious difference that the maneuver is vertical unlike the horizontal maneuvers that are used in the other scenarios, is that Flight 1 continues on its cleared trajectory for four minutes before temporarily leveling off. The reason for this is, operationally, a controller will not level off a flight until it reaches its highest altitude possible. Since the air is less dense at higher altitudes, less fuel is consumed by the aircraft assuming the flight is constant. This does not occur for the direct-to resolutions because they maintain the same rate of climb and, hence, the same altitude in each of the scenarios.

It is important to analyze how the differences in the action time parameter affect certain statistics such as fuel consumption or delay. Table 23 shows, as expected, that the vertical maneuver results in more fuel burn than the baseline flight whereas the direct-to maneuvers report a fuel savings. Also, the earlier a direct-to is started, the greater the fuel savings for the flight. Additionally, the delay that results from the maneuvers increases as the action time increases. This is also expected because more time between the maneuver start time and the conflict start time, the more efficient the resolution can be, especially if it is a horizontal maneuver.

Table 23: Example 2 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	Vertical	8	1	144.96	-20
7	Direct-To	7	6	-55.25	-43
9	Direct-To	8	8	-117.72	-89
11	Direct-To	7	10	-177.28	-128

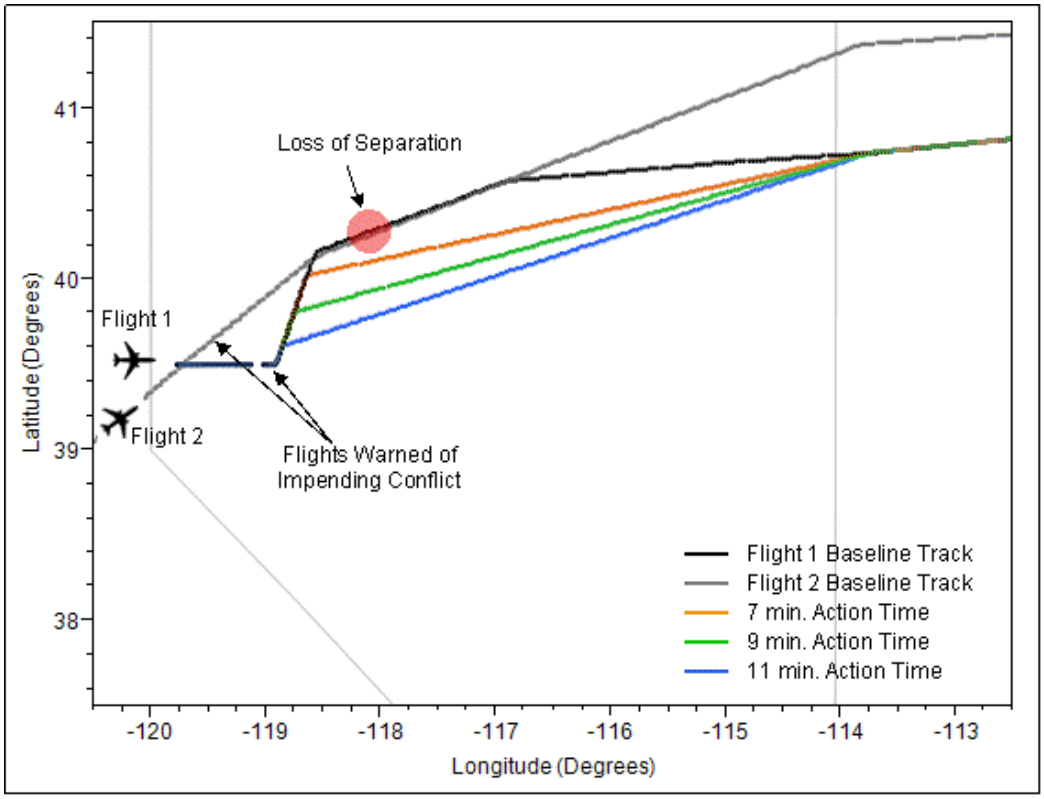


Figure 45: Example 2 - Horizontal Flight Tracks

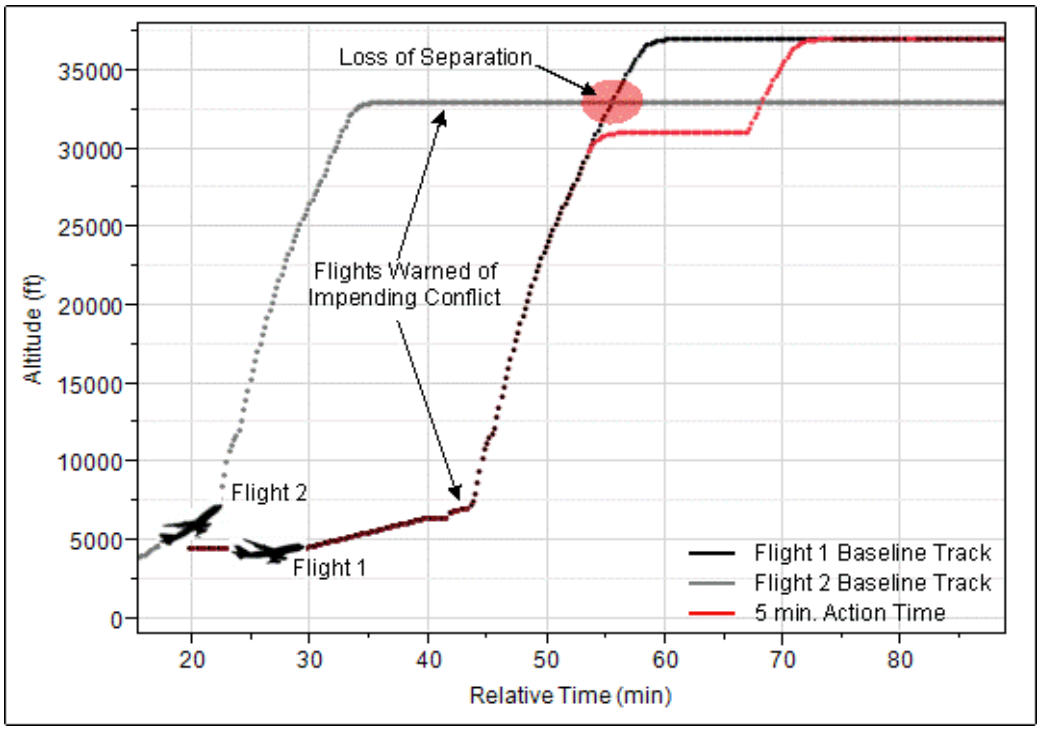


Figure 46: Example 2 - Vertical Flight Tracks

3.2.3.3 Example 3

Figure 47 shows the flight paths of the two conflicting flights in the horizontal domain for Example 3. This example analyzes two flights in a crossing conflict and how Flight 1 is maneuvered 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 (KORD) and Charlotte/Douglas International Airport (KCLT). Flight 2 is a Boeing 737-800 aircraft that is en route from Newark-Liberty International Airport (KEWR) to Los Angeles International Airport (KLAX). As with the previous example, Flight 1 is climbing to its cruising altitude when it encounters Flight 2, which is already at its cruise altitude.

This encounter, as depicted in Figure 47, occurs in the central region with 2020 traffic levels. As previously mentioned, it is a crossing conflict with an encounter angle of 119.6° and the detection time for the flights in this scenario is 760 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. Flight 1 is climbing to 37,000 feet while Flight 2 is cruising at 36,000 feet; the two flights do not lose separation until Flight 1 has climbed to 36,900 feet which is higher than the cruise altitude of Flight 2.

It is clearly illustrated that the action time parameter affects the maneuvers used in these four scenarios. All four maneuvers are direct-to maneuvers that depart the cleared route at different times depending on the action time of the scenario. Table 24 shows that, like the previous two examples, as the action time parameter increases, the fuel consumption decreases. Additionally, as expected, all four direct-to maneuvers result in a fuel consumption savings as well as a negative value of delay (i.e. a gain). Regardless of whether the maneuvers result in a delay or a gain, it is clear that an increased action time can be very beneficial in terms of reducing both the fuel consumption and delay.

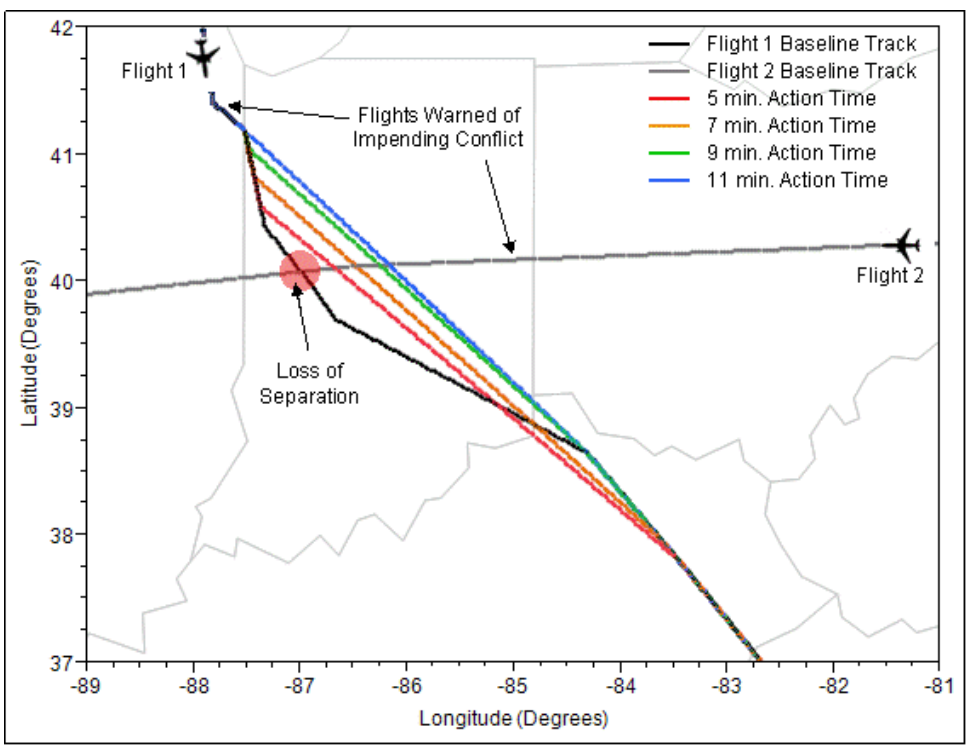


Figure 47: Example 3 - Horizontal Flight Tracks

Table 24: Example 3 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

3.2.3.4 Example 4

This example of a conflict occurs in the west 2018 scenarios. An Airbus 320 and Boeing 737 descending into McCarran International Airport in Nevada (KLAS) come into conflict. The flights' origins are Philadelphia International Airport (KPHL) and Louisville International Airport (KSDF), respectively. The flight from Louisville is maneuvered horizontally to resolve the conflict in all four action time scenarios. This flight is labeled as Flight 1 in Figure 48, which depicts horizontal flight tracks for both baseline flights and variations from each action time scenario.

The conflict is detected 19min and 35 seconds before the anticipated time of first loss. The location of the two aircraft at this detection time is indicated in Figure 48 as "Flights Warned of Impending Conflict." The time period during which the flights would have experienced a loss o separation is 125 seconds, and the encounter angle is 1.3°. The conflict altitudes are 10,000 feet for Flight 1 and 10,928 feet for Flight 2.

Table 25 presents relevant information for this conflict compared across the four different action time scenarios. Because the detection time of this conflict was well in advance of the time of first loss, strategic resolution maneuvers were able to be implemented. Each resolution in the various action time scenarios is the end result of different constraints that vary with the time remaining before conflict. With more time there are better options for maneuvering a flight to avoid conflict, especially in the horizontal direction. The resolution maneuver in the 11-minute action time scenario is the most fuel and time efficient and represents the most strategic approach. The pattern of better fuel and time efficiency with larger action times is observed consistently in the four resolutions for this example.

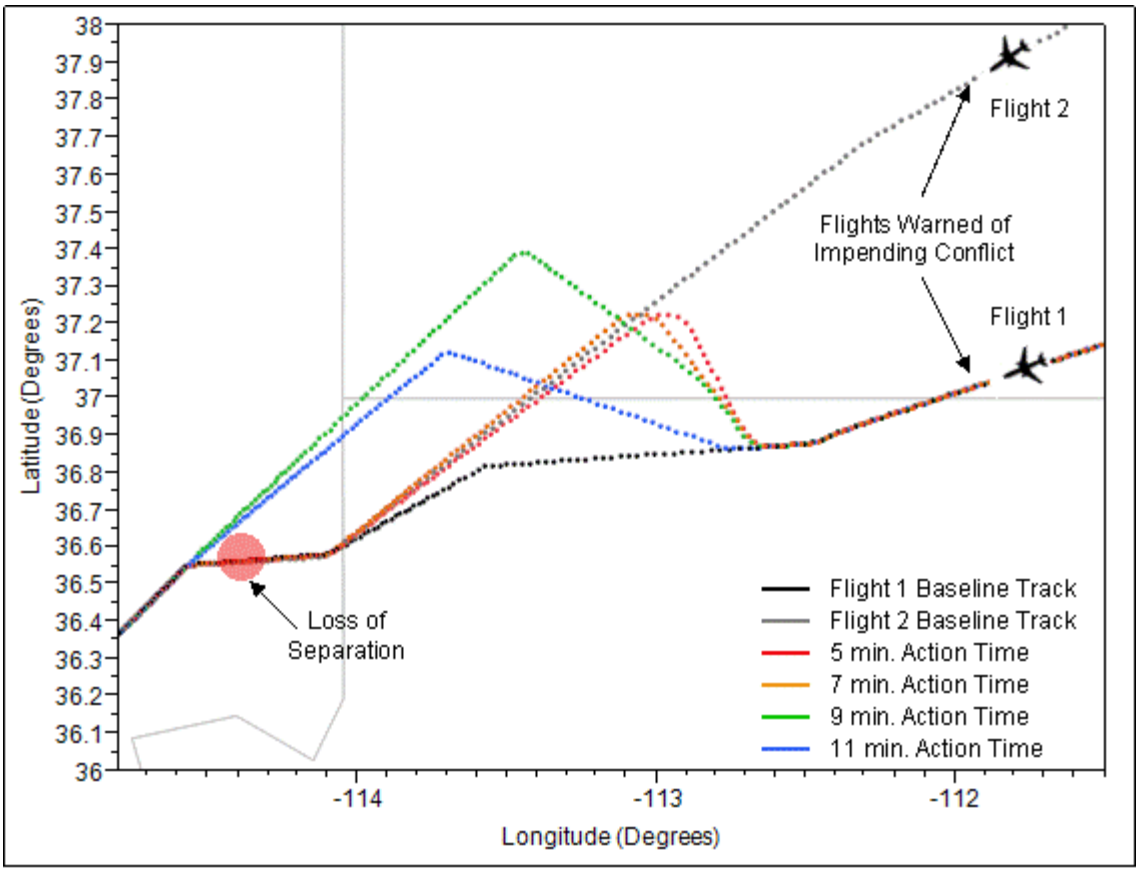


Figure 48: Example 4 - Horizontal Flight Tracks

Table 25: Example 4 Conflict Statistics

Action Time (min)	Resolution Type	Number of Options	Additional Fuel Consumed (lbs)	Maneuver Delay (sec)
5	Std. Horizontal	6	238.19	105
7	Std. Horizontal	6	226.93	103
9	Std. Horizontal	5	123.92	94
11	Std. Horizontal	5	-19.05	86

3.2.3.5 Example 5

This example shows two flights flying in the central 2025 scenarios where Flight 1 is maneuvered to avoid a conflict with Flight 2 using a path stretch maneuver for each of the four action time parameter scenarios. In this example, Flight 1 is a Boeing 737 climbing to its cruise altitude of 37,000 feet. from Chicago Midway International Airport (KMDW) on its way to Philadelphia International Airport (KPHL). Flight 2 is an Airbus A319 descending to O'Hare International Airport (KORD) in Chicago at the end of a flight departing from Ronald Reagan Washington National Airport (KDCA). Figure 44 shows that the conflict is a crossing conflict with an encounter angle of 118.9° that occurs over the southern tip of Lake Michigan.

The conflict depicted in Figure 49 occurs when both flights are at 13,500 feet (Flight 1 is ascending while Flight 2 is descending) are the four treatment routes that ACES assigns to Flight 1 for each of the action time parameters. The conflict is detected right as Flight 1 enters the scenario, so the detection time is only 70 seconds. Since the detection time is so short, a maneuver needs to be assigned immediately, rendering the action time irrelevant in this example. It is curious, however, that each scenario is not assigned the same exact resolution. The reason for this is because each of the four scenarios is not exactly the same; there is a slight uncontrollable variability that is inherent in ACES that sometimes results in cases that are unexpected. The difference in these maneuvers is simply due to this randomness. However, this example shows that this variability is miniscule and has little effect on the simulation as a whole.

Despite the fact that all the resolutions leave and return to the cleared route at the same time, Table 26 reports that the scenarios result in the expected benefit (i.e. decreasing fuel consumption and delay as a function of an increasing action time). Since Flight 1 is maneuvered at the same time in all of the treatment scenarios, it is a coincidence that this trend occurs in the data. In a perfect, controlled environment, the maneuver would be exactly the same in all four treatment scenarios and the delay and additional fuel consumption would be the same for each action time. This further proves the point that the most benefit for the proposed changes occurs at higher detection times.

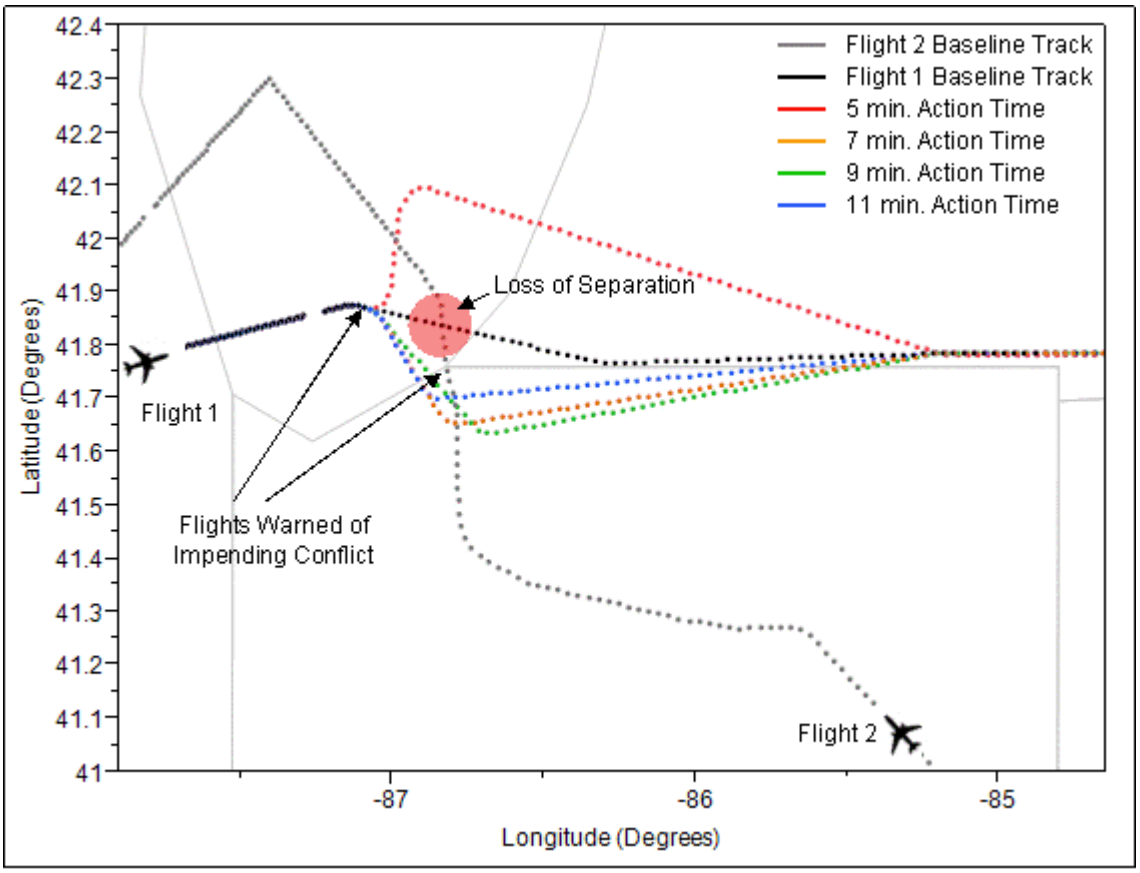


Figure 49: Example 5 - Horizontal Flight Tracks

Table 26: Example 5 Conflict Statistics

Action Time (min)	Resolution Type	Number of Options	Additional Fuel Consumed (lbs)	Maneuver Delay (sec)
5	Std. Horizontal	4	108.84	95
7	Std. Horizontal	4	51.81	49
9	Std. Horizontal	4	61.26	45
11	Std. Horizontal	4	46.62	36

3.2.3.6 Example 6

This example documents a conflict that occurs in the central 2018 scenarios where a vertical resolution is used in all four action time scenarios. Flight 1, which is the flight that is maneuvered to avoid the conflict, is a Canadair Regional Jet CRJ-200 taking off from Cincinnati/Northern Kentucky International Airport (KCVG) going west to Kansas City International Airport (KMCI). Flight 2, on the other hand, is McDonnell Douglas MD82 flying at a cruising altitude of 33,000 feet between Dallas-Fort Worth International Airport (KDFW) and La Guardia Airport in New York City. The horizontal baseline flight paths for the two flights are depicted in Figure 50, which shows that the flights are a crossing conflict with an encounter angle of 148.9°.

Figure 51, which depicts the vertical tracks of both flight paths and, consequently, the resolutions used for each action time parameter, shows that Flight 1 levels off at the same altitude regardless of the action time parameter. Flight 1 has climbed to 32,500 feet when separation is lost while Flight 2 is at its cruising altitude of 33,000 feet. When the conflict is detected, AAC waits until the highest altitude possible before leveling off Flight 1 because it is more fuel and time efficient than leveling off at a lower altitude where the air is more dense. This is consistent with the procedures that air traffic controllers follow operationally and a practice that is integral to using vertical resolutions. Since ACES will always try to prevent maneuvering the flight until it reaches its highest altitude possible, it can be expected that the benefit of a longer action time will not have as pronounced an effect on vertical maneuvers as it would on horizontal maneuvers. This is evident in the difference in benefit between the examples that use horizontal maneuvers and those that display vertical maneuvers.

Table 27 shows that as the action time increases, the additional fuel consumed over the baseline run increases while the maneuver delay decreases. The increasing fuel consumption is the opposite effect that is expected as the action time increases. This is especially true since the conflict has a relatively large detection time of 13 minutes and 5 seconds, which is greater than any of the action time parameters. However, there are two aspects of the data that seem to be inconsistent with expectations. First, there should not be any gain that results from this maneuver since Flight 1 is flying a portion of its route at a lower altitude than expected and second, it is expected that the four resolutions should be exactly the same but they are not returning to the cleared route at the same time. All of this indicates that there is something else happening when Flight 1 undergoes its maneuver.

To investigate this conflict further, Figure 52 shows the calibrated air speed, the ground speed, and the altitude all as a function of time. As the two speed charts show, the flight increases its speed when it levels off, causing the increasing fuel consumption and the negative delay values. Also, although it is not shown in any of these charts, the level-off time for this scenario is the same as the value of the action time. Therefore, in the five-minute scenario, Flight 1 is leveled off for five minutes before ascending back to its cleared route. This explains why the vertical flight path for each action time scenario is different.

Unfortunately, neither of these deficiencies is uncommon for the vertical maneuvers in the scenarios. When ACES levels off a flight temporarily, it will mistakenly try to make the switch from calibrated airspeed to mach airspeed causing the increase in speed. While the fuel consumption differences that result from this defect are small relative to the total amount of fuel burned (e.g. for Flight 1 in this example, roughly 20 pounds compared to the 3,100 pounds it burns over the course of its entire flight), it is important to keep this flaw in mind when analyzing the data. Further investigation could be done on solely vertical maneuvers so see the true effect the differing action times have on the fuel consumption and delay

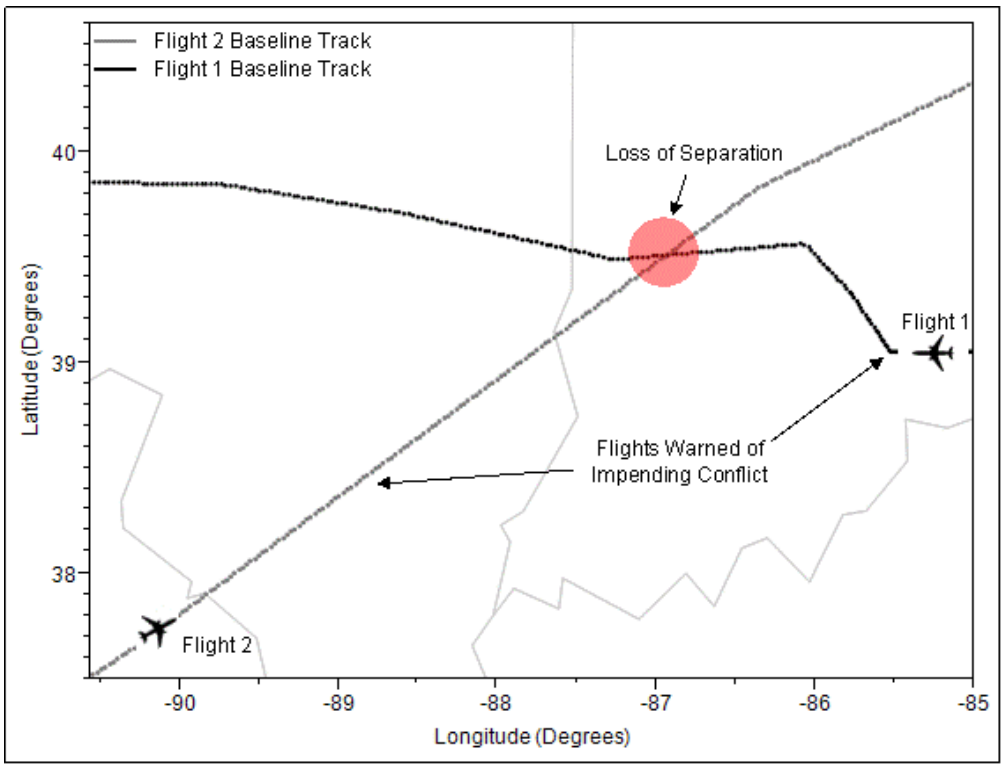


Figure 50: Example 6 - Horizontal Baseline Tracks

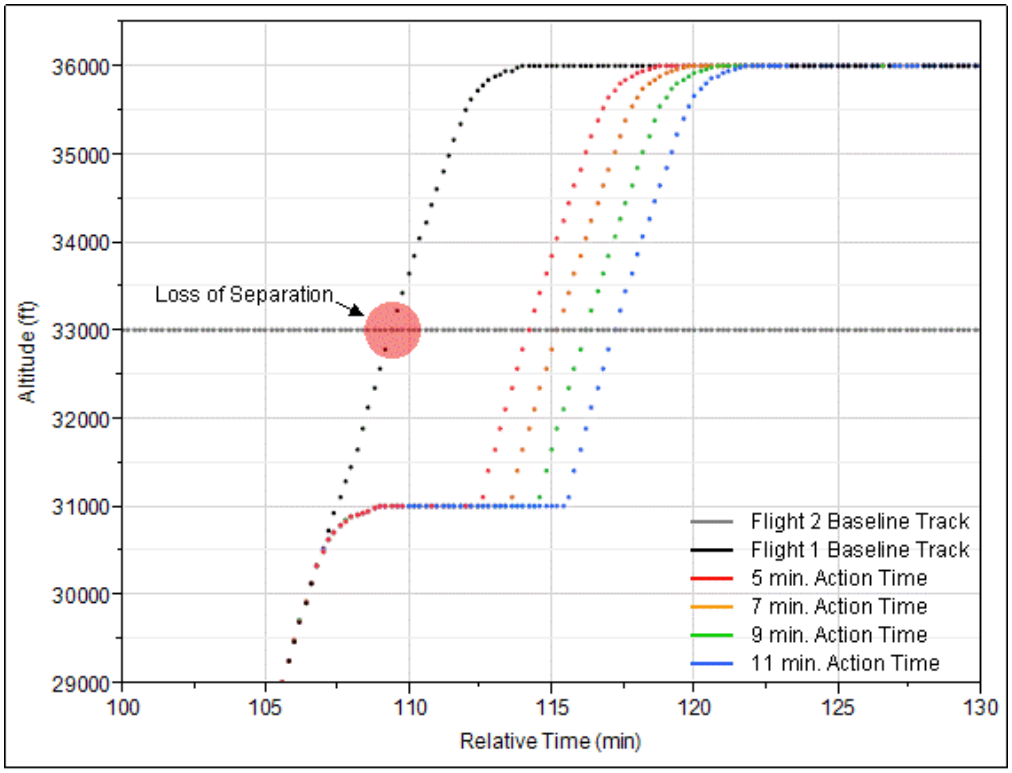


Figure 51: Example 6 - Vertical Tracks Changing as a Function of Action Time

Table 27: Example 6 Conflict Statistics

Action Time (min)	Resolution Type	Number of Options	Additional Fuel Consumed (lbs)	Maneuver Delay (sec)
5	Vertical	7	21.86	-7
7	Vertical	7	28.17	-8
9	Vertical	7	34.74	-10
11	Vertical	8	37.26	-12

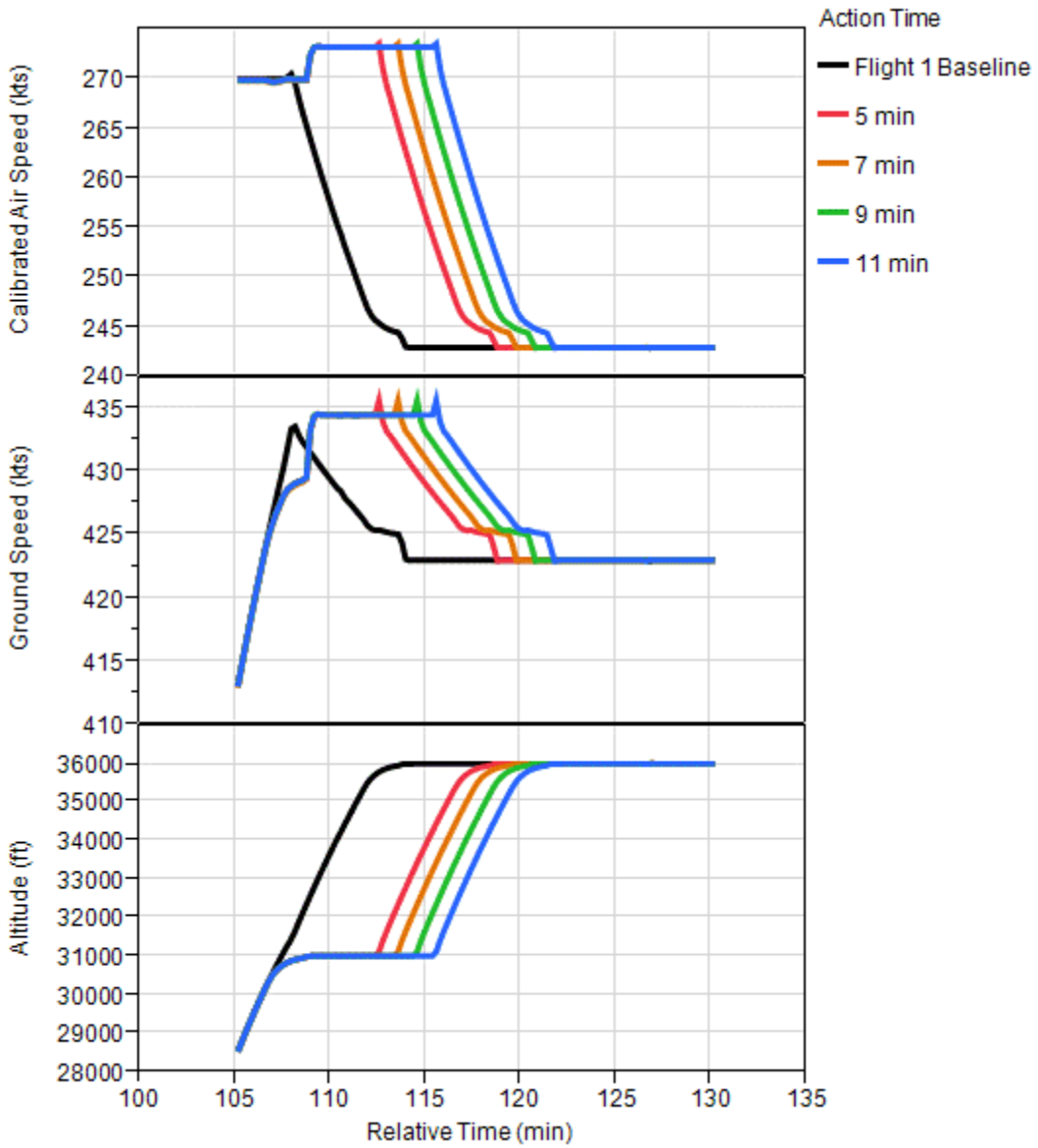


Figure 52: Example 6 - Changes in Speed

3.2.3.7 Example 7

This example documents a conflict that occurs in the west-2025 scenarios. Flight 1 is a Boeing 737-800 taking off from Sacramento International Airport (KSMF) while Flight 2 is a Cessna Citation X taking off from McClellan Airfield (KMCC), which is also located in Sacramento. As shown in Figure 53, both flights are heading east and since their takeoff times are only about 90 seconds apart, they approach each other at an angle of 2.3°, making the conflict an in-trail conflict.

The two flights in this scenario are warned of the conflict 6 minutes, 5 seconds before the loss of separation, so only the 5-minute action time scenario occurs after the detection time. The other three scenarios are free to maneuver the flights as soon as the warning is issued. This is reflected in Figure 54, which shows the vertical tracks for the baseline scenario for both flights as well as for the four treatment runs. As shown in the figure, the seven, nine, and 11-minute action time scenarios start Flight 1's maneuver at the detection time, whereas the five-minute scenario continues to fly Flight 1 to its highest possible altitude before temporarily leveling it off.

There are a few ACES deficiencies on display in this figure. First, operationally, controllers will always climb a flight to its highest altitude possible before instituting a maneuver. This allows the flight to fly in air that has as small a density as possible, thus conserving time and fuel. It is somewhat uncommon that this occurs in the simulations, but it is worth keeping in mind because it does happen occasionally. Second, if the seven, nine, and 11-minute scenarios are leveling off at the same time, it should be expected that the maneuvers will be identical (i.e. they will return to the route at the same time). When ACES performs a temporary leveling-off maneuver, the amount of time the flight is leveled off is the same as the action time of the scenario. For example, the nine-minute action time maneuver will level off for nine minutes before starting its ascension back to its cleared route. This is why those three maneuvers return to the cleared altitude at different times.

As the action time parameter increases, it is expected that the fuel consumption and the maneuver delay both decrease; Table 28 reflects these trends for this example. While the fuel consumption looks as it should (except for the fact that ideally, the seven, nine, and 11-minute scenarios should be exactly the same, so their fuel consumption should be identical), it is curious that the four maneuvers actually result in a gain. If a flight is flying at a lower altitude than expected, in denser air, the maneuver should result in a delay. The reason for this is explained in Section 3.2.3.6 and displayed in Figure 55. When ACES levels off a flight temporarily, it will attempt to change its speed measuring system from calibrated airspeed to mach and, consequently, increase the speed of the flight. This does not happen operationally, but happens in every situation in ACES where a flight is leveled off during its climb. This is the reason for the unexpected gain in time that Flight 1 undergoes in each scenario. Therefore, this should be kept in mind when analyzing the fuel consumption and delay of the systems overall.

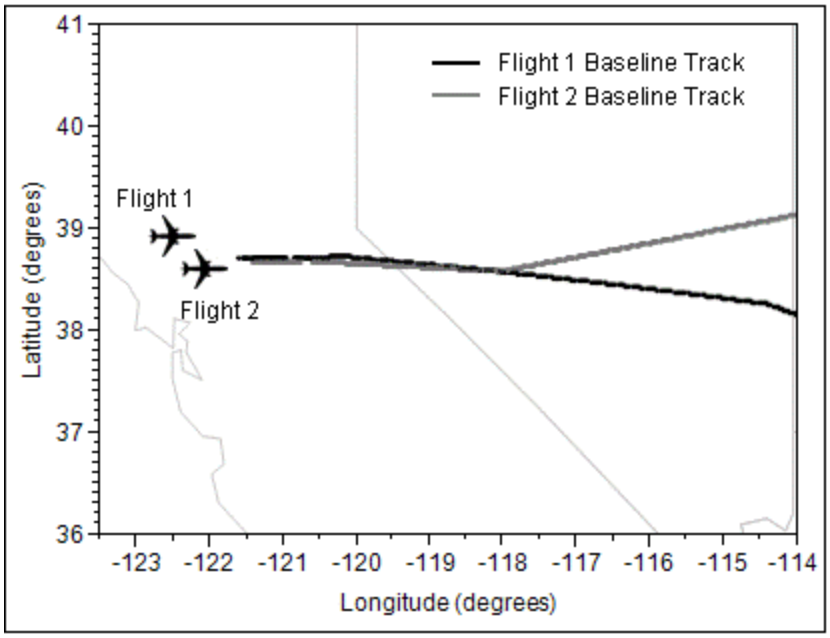


Figure 53: Example 7 - Horizontal Baseline Tracks

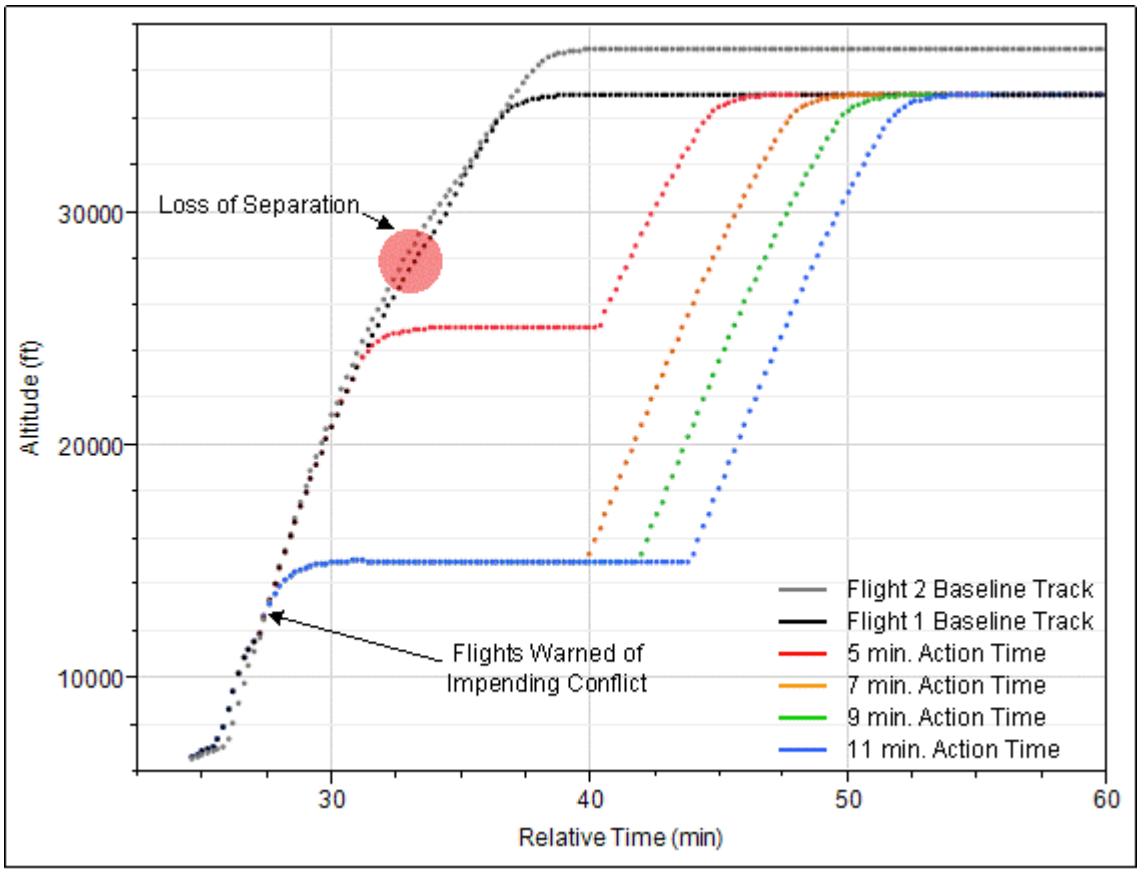


Figure 54: Example 7 - Vertical Tracks Changing as a Function of Action Time

Table 28: Example 7 Conflict Statistics

Action Time (min)	Resolution Type	Number of Options	Additional Fuel Consumed (lbs)	Maneuver Delay (sec)
5	Vertical	7	168.75	-14
7	Vertical	8	701.66	-56
9	Vertical	8	859.40	-67
11	Vertical	8	1007.03	-77

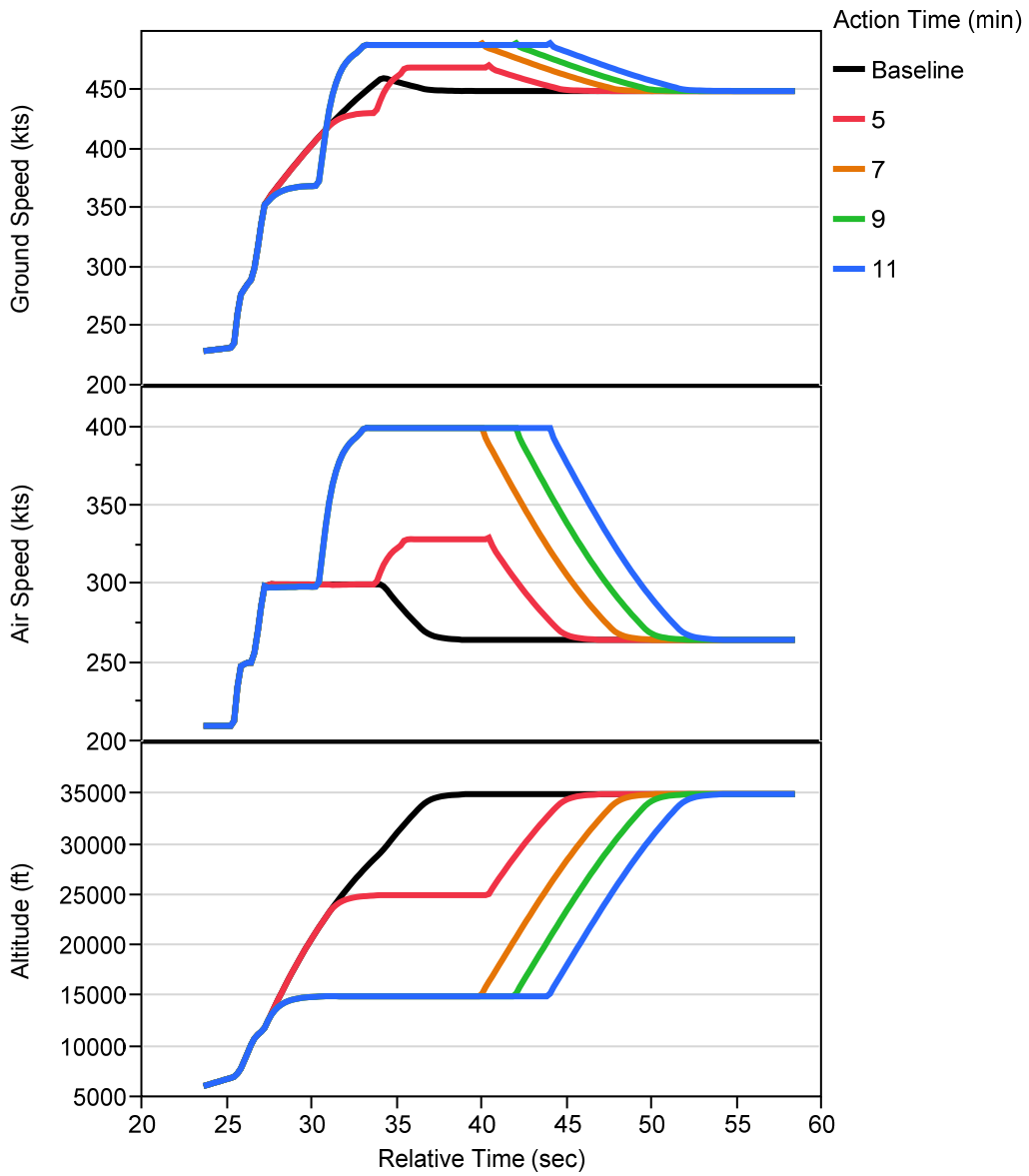


Figure 55: Example 7 - Changes in Speed

3.2.3.8 Example 8

This example displays two flights in the central 2018 scenarios that are projected to lose separation during their respective cruise phases of flight. Flight 1 is a Canadair Regional Jet CRJ-200 that is en route between Hartsfield-Jackson Atlanta International Airport (KATL) and Cleveland Hopkins International Airport (KCLE). Flight 2, meanwhile, is a Boeing 757-200 twin jet that is en route from Cincinnati/Northern Kentucky International Airport (KCVG) to O'Hare International Airport (KORD) in Chicago, IL. As shown in Figure 56, the flights approach each other at an encounter angle of 100.3°, making this a crossing conflict.

The detection time for this conflict is 14 minutes and 40 seconds, which is greater than any of the action time parameters. This means that the resolution can start as soon as the action time parameter is reached in all four treatment scenarios. This conflict is resolved using a speed maneuver; ACES/AAC increases the speed of Flight 1 before it reaches the point of conflict so that minimum separation between the two flights is never violated. The speed-versus-time profiles for the baseline and treatment scenarios are shown in Figure 57. As the figure shows, the resolution starts earlier as the action time parameter increases; the resolution starts in the 11-minute scenario before it starts in the nine-minute scenario, the resolution in the nine-minute scenario starts before it starts in the seven-minute scenario, etc. It is interesting that Flight 1 in the 11-minute scenario returns to its original speed before it returns in the other three treatment scenarios. This is most likely caused by the fact that since Flight 1 increases its speed earlier in the 11-minute action time scenario than in the other three, it clears the conflict earlier and can return to its baseline speed. Since it is required that Flight 1 remains conflict free for 12 minutes, ACES must wait approximately 90 seconds longer before returning Flight 1 to the cleared baseline speed in the three remaining scenarios.

Table 29 reveals two expected results from a speed-increase resolution: an increase in fuel consumption and a decrease in delay. Since the nine- and 11-minute scenarios increase the speed of Flight 1 for the same amount of time, it would be expected that the maneuver delay and the fuel consumption would be almost the same, which Table 29 illustrates. Similarly, one would anticipate that the 7-minute scenario would have more fuel consumption than the five-minute scenario since the speed is increased for a longer duration of time. Overall, the numbers are somewhat erratic but there seems to be a slight benefit in both fuel consumption and maneuver delay for this speed-increase maneuver.

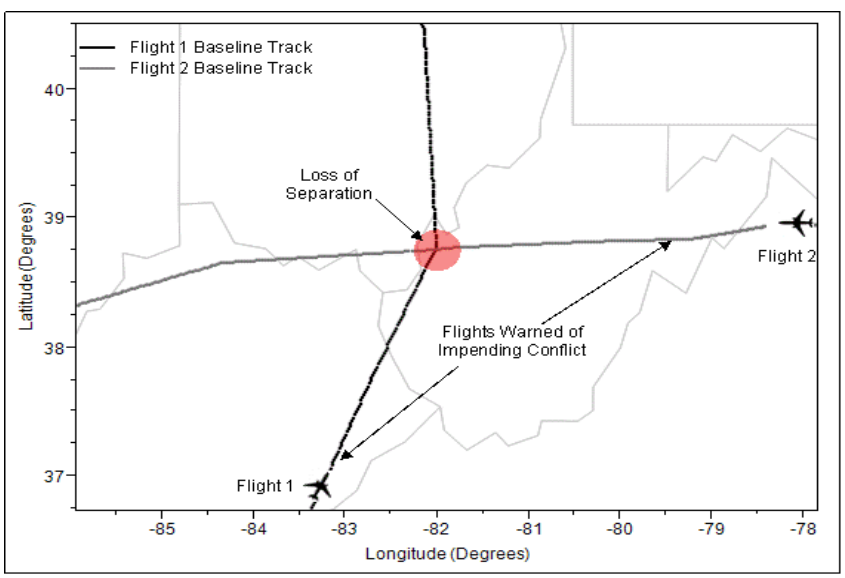


Figure 56: Example 8 - Horizontal Flight Tracks

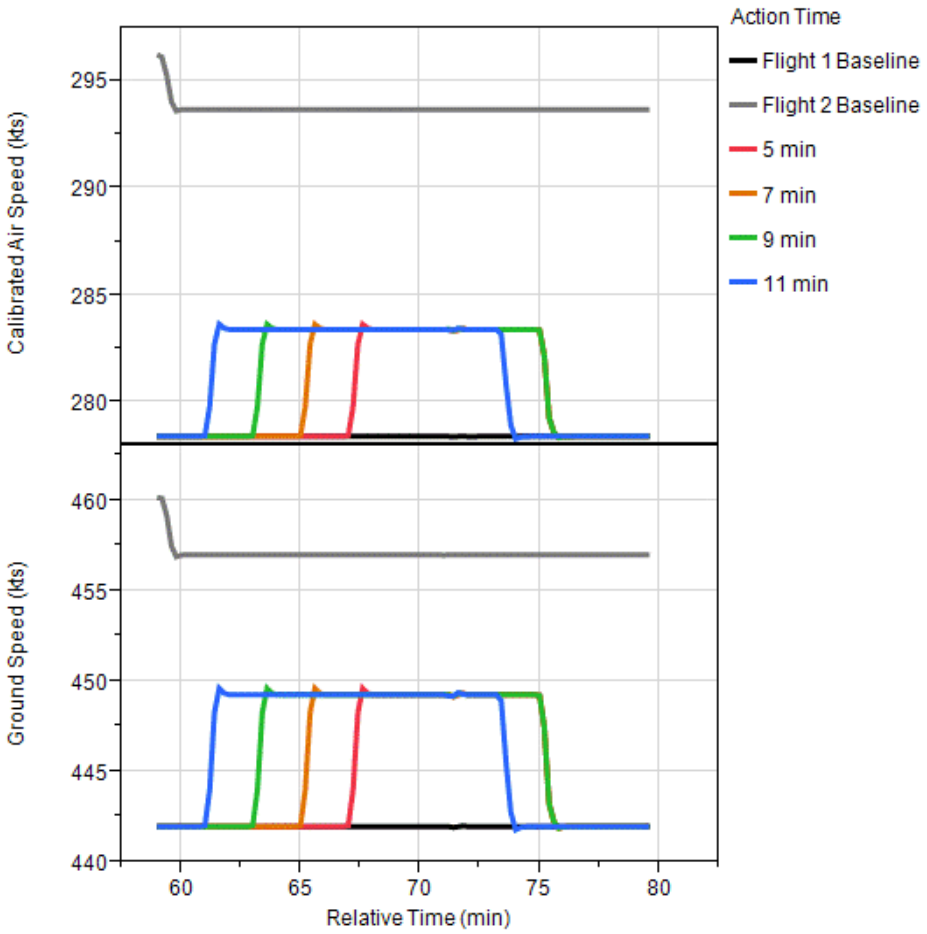


Figure 57: Example 8 - Speed During Maneuver of Flight 1

Table 29: Example 8 Conflict Statistics

Action Time (min)	Resolution Type	Number of Options	Additional Fuel Consumed (lbs)	Maneuver Delay (sec)
5	Speed	10	11.05	-8
7	Speed	10	14.16	-10
9	Speed	10	5.88	-12
11	Speed	9	6.32	-12

4. Study Conclusions

CRA is envisioned as an advanced decision support tool for air traffic control deployed within the NextGen TBO initiatives. 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, as defined in Section 1.3, is 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. This technical note estimates these potential benefits by using the advanced ACES/AAC fast-time simulation platform and applying four key metrics. The first three metrics or response variables include the percentage difference of fuel, flight distance, and flight time of a baseline flight without any maneuvers. The fourth metric is the estimated maneuver delay time associated with each resolution maneuver modeled.

An action time parameter was incorporated into the ACES/AAC simulation platform that limits the lead time that a resolution maneuver can be implemented during the run. The details are described in Section 2.2.2.3 with several examples provided in Section 3.2.3. Other factors included are the three airspace regions of east, central, and west (see Section 2.2.2.2 for complete definition) and three forecast traffic years of 2018, 2020, and 2025 (see Section 2.2.2.1 for additional details). The combinations were run through the ACES/AAC fast-time simulation platform and results summarized in Table 30. Three experimental models were fit to the simulation results. Model 1 establishes the basic experimental approach. Model 2 provides the overall results and Model 3 partitions the results by the four resolution maneuver types. Based on Model 2, fuel consumption is reduced (i.e., % fuel burn impact decreases) as action time increases when warning time is high. The opposite is true when warning time is low. When considering resolution maneuver type as a factor under Model 3, only direct-to maneuvers consistently provide a reduction in fuel consumption, while vertical maneuvers have the opposite effect. For both horizontal and speed maneuvers, the benefit is marginal. For maneuver delay time, the benefit improves (delay time decreases) as action time increases for all levels of warning time and maneuvers.

Table 30: Summary of Experimental Results

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
	3.2.3.3, 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, ***Increase*** as Action Time Increases when Warning Time Low	***Decrease*** as Action Time Increases for both Low and High Warning Times

Table 30 summarizes the net results of the study. To further illustrate these results and show the magnitude of the effects, a set of 3-D surface plots were generated for % fuel burn impact and maneuver delay responses. Model 3's results for action times and maneuver are presented in Figure 58 and Figure 59, for % fuel burn impact and maneuver delay, respectively. For Figure 58, the 3-D plot shows the net change of % fuel burn impact for each maneuver type. This translates to an average increase in % fuel burn 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%. These are observed model effects at particular airspace and warning times. Table 35 in Appendix B provides the coefficient estimates of Model 3 overall (e.g. direct-to maneuver is -0.8% and vertical is 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 59 with a negative slope for all four types. As expected, and consistent with fuel burn, the direct-to and vertical maneuvers have the steepest slope representing the largest effects.

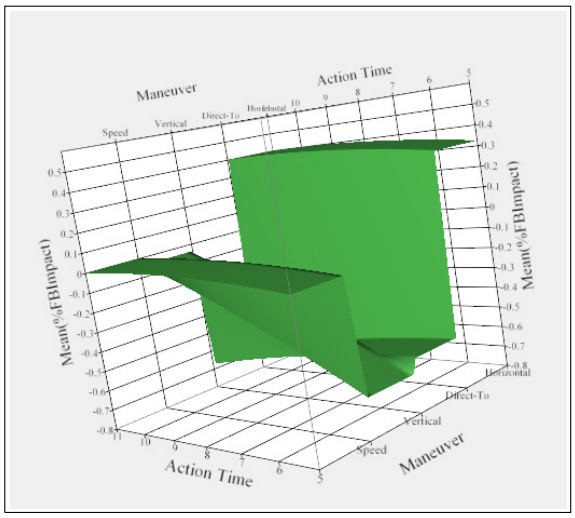


Figure 58: Surface Plot of %FB Impact by Maneuver Type and Action Time from Model 3

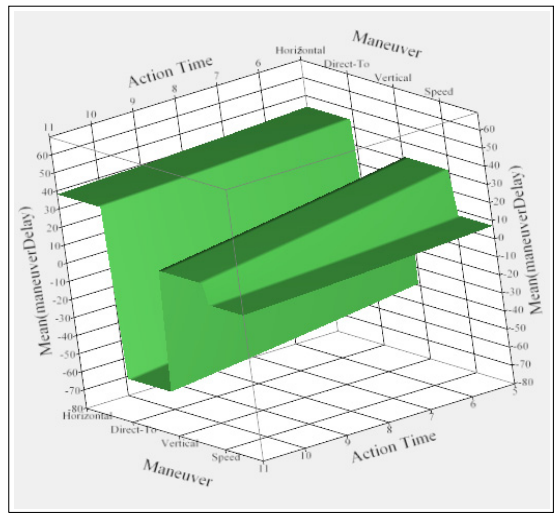


Figure 59: Surface Plot of Maneuver Delay Time by Maneuver Type and Action Time from Model 3

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 58 shows that horizontal maneuvers have the highest average followed by speed maneuvers. 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 59, horizontal and vertical maneuvers have the highest average delays in the 30-40 second range, while direct-to has a negative maneuver delay time on average ranging from -40 to -60 seconds. Thus, this indicates that performance differs depending on the maneuver type and also varies as a function of action time.

For the overall results of Model 2 without conditioning on maneuver type, Figure 60 illustrates the % 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 % fuel burn impact increases by about 1% as a function of action time. At higher warning times (greater than 11 minutes) it decreases non-linearly by about 0.3% overall. This relationship of action and warning times is further demonstrated by the eight flight examples in Section 3.2.3 and referenced in Table 30.

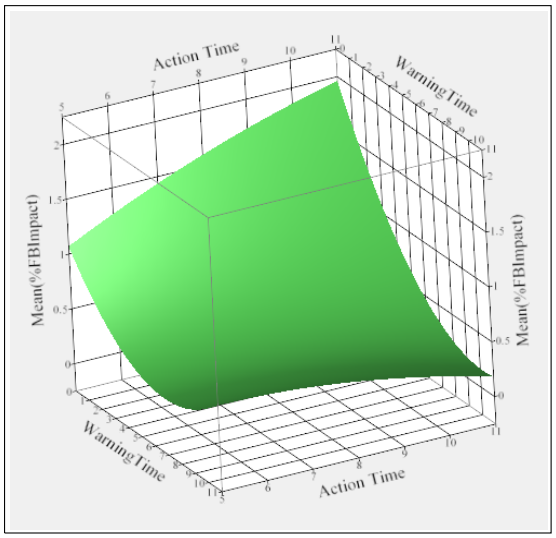


Figure 60: Surface Plot of %FB Impact by Action Time and Warning Time from Model 2

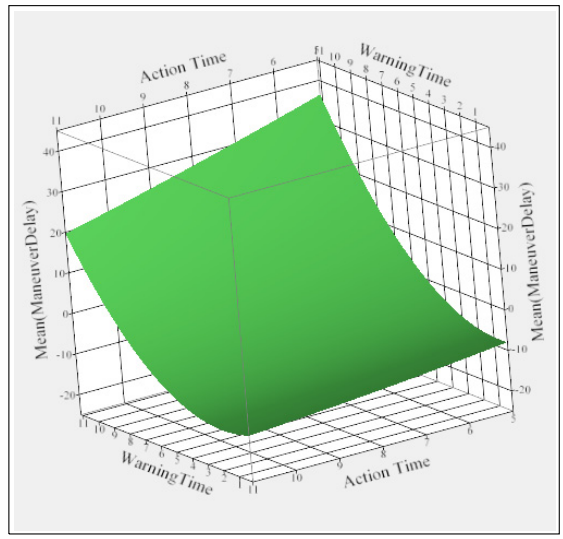


Figure 61: Surface Plot of Maneuver Delay Time by Action Time and Warning Time from Model 2

Figure 61 illustrates 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). It shows that at high warning time (greater than 11 minutes) the maneuver delay decreases rapidly from about 37 to 20 seconds as action time increases. The figure 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. At lower warning times, the average % fuel burn impact is higher, ranging between 1% and 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.

To summarize, fuel consumption is reduced when resolutions are solved more strategically (i.e., action time is larger) but only when the warning time of the conflict is sufficiently large; otherwise it is a tactical situation and acting more strategically does not apply. The resolution geometry or maneuver type is another important consideration and based on the ACES/AAC model, direct-to maneuvers provide the only consistent benefit as a function of action time.

5. Recommendations for Future Studies

To support the development of the CRA Project, this study investigates the benefits of more efficient maneuvering due to more strategic controller actions. This is one of a series of studies to estimate a number of potential benefits of CRA (see Section 1.3 for a full listing). Being the first in the series, 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. However, a number of lessons learned should be documented for later studies to build upon. They 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 should be investigated and improved upon. For example, the internally developed fuel burn calculator tool had some either incorrect aircraft mappings or aircraft characteristics that were in error. Additional resources are currently investigating these issues and will correct some of the issues encountered in this study.
- 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.
- Conflict resolutions were applied to aircraft that were detected to have conflicts. Flights selected and resolved for one conflict could be selected again for another. The basic percentage impact measurements compared a baseline run without any maneuvers to the treatment runs with conflict resolutions applied. Therefore, the flight's fuel, distance, or time difference compared to the baseline could easily be attributed to the maneuver if a single maneuver was applied. If however the flight had multiple maneuvers, it is much more difficult to attribute this difference to each of its maneuvers due to their confounding. Thus, future analyses need to develop techniques to partition the impact of multiple maneuvers and include all flight's conflict resolutions in the analysis.
- As summarized in Section 3.2.2.2.4 and illustrated in Figure 42, vertical maneuvers had a negative benefit (cost) associated with them in terms of fuel burn impact as a function of increasing action time. This was not the expected benefit. This result was explained further in Example Flights 6 and 7 documented in Sections 3.2.3.6 and 3.2.3.7, respectively. The ACES/AAC vertical maneuver speed profile and temporary altitude level off time is attributed to the counter intuitive results. Thus, a detailed examination of this phenomenon in ACES/AAC vertical maneuver modeling is recommended prior to future studies using the tool.
- As described in Section 2.2.2.3, action time and warning time are key factors of the study. Action time being a controlled factor for each treatment run ranging from 5 minutes to 11 minutes, while warning time ranged from 0 to 20 minutes, which is dependent on the geometry of the particular conflict detected and resolved. The 11 minute upper bound for action time was selected based on the 12 minute threshold used in the CRA operational evaluations. However, follow-up runs are recommended at larger thresholds including the upper absolute bound of 20 minutes. This would provide further evidence on the boundaries that the potential benefit of strategic maneuvering can achieve.
- Additional validation and possible calibration of the ACES/AAC conflict resolution maneuvers to operational resolutions is warranted. Previous studies such as described in Ref. [2] and [3] are relied upon for this initial study. Further examination of the AAC's resolutions compared to operational solutions is recommended. The results could serve to confirm the conclusions of the study or future studies based on the modeled resolutions. It could also be used to calibrate the simulation platform for future studies.

6. Glossary

AAC	Advanced Airspace Concept
ACES	Airspace Concept Evaluation System
AJP-661	FAA's Simulation and Analysis Team
ANSP	Air Navigation Service Provider
ARC	Ames Research Center
ARTCC	Air Route Traffic Control Center
AJG	FAA's Joint Planning Group
ATO-P	Air Traffic Organization – NextGen and Operations Planning Office
BADA	Base of Aircraft Data
CONUS	Continental United States
CP	Conflict Probe
CRA	Conflict Resolutions Advisories
Datacomm	Data communications
DOE	Design of Experiment
DOF	Direction of Flight
DST	Decision Support Tool
ETMS	Enhanced Traffic Management System
FAA	Federal Aviation Administration
FB	Fuel Burn
FD	Flight Delay
FDS	Flight Data Set
FT	Flight Time
FY	Fiscal Year
IFR	Instrument Flight Rules
JPDO	Joint Planning Development Office
MySQL	The MySQL® open source relational database system
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System
OPSNET	Operations Network
PLA	Project Level Agreement
TAF	Terminal Area Forecast
TBO	Trajectory-Based Operations
TRACON	Terminal Radar Approach Control
UTC	Coordinated Universal Time
VFR	Visual Flight Rules
VHF	Very High Frequency
ZAU	Chicago ARTCC
ZBW	Boston ARTCC
ZID	Indianapolis ARTCC
ZLA	Los Angles ARTCC
ZNY	New York ARTCC
ZOA	Oakland ARTCC

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8. Appendix A

The Appendix A provides additional descriptive statistics for the conflict resolutions for the various airspace regions, action times, and years. Table 31, Table 32, and Table 33 provide the statistics for forecast years 2018, 2020, and 2025, respectively.

Table 31: Overview of Conflict Resolution Statistics for 2018 Scenarios

	Metric (No) / Action Time	Number of Cfls. (1)	Conflict Density (2)	Avg. # Options per Cfl. (3)	Horz. Res. (4)	Direct-To Res. (5)	Vert. Res. (6)	Speed Res. (7)	Total Delay in minutes (8)
East	5-min	2,430	0.32	7.18	9.9%	34.0%	22.5%	33.6%	37,362
	7-min	2,438	0.32	7.26	11.2%	32.4%	23.1%	33.3%	27,266
	9-min	2,435	0.32	7.30	12.2%	32.9%	21.1%	33.8%	26,669
	11-min	2,565	0.34	7.28	10.5%	32.6%	21.1%	35.8%	31,006
Central	5-min	4,749	0.51	7.27	11.5%	24.1%	21.1%	43.4%	67,166
	7-min	4,848	0.52	7.23	13.1%	23.8%	21.4%	41.6%	63,185
	9-min	4,906	0.53	7.28	13.2%	24.8%	21.3%	40.7%	60,014
	11-min	4,992	0.54	7.33	12.7%	24.9%	21.8%	40.6%	60,322
West	5-min	3,037	0.46	6.98	7.6%	29.2%	28.3%	28.3%	51,715
	7-min	3,201	0.49	6.88	7.7%	32.0%	26.5%	26.5%	62,861
	9-min	3,112	0.47	7.01	8.4%	29.9%	26.7%	26.7%	50,127
	11-min	3,159	0.48	7.08	7.9%	30.2%	26.0%	26.0%	49,739

Table 32: Overview of Conflict Resolution Statistics for 2020 Scenarios

	Metric (No.) / Action Time	Number of Cfls. (1)	Conflict Density (2)	Avg. # Options per Cfl. (3)	Horz. Res. (4)	Direct-To Res. (5)	Vert. Res. (6)	Speed Res. (7)	Total Delay in minutes (8)
East	5-min	2,573	0.33	7.18	10.1%	33.0%	22.2%	34.6%	35,535
	7-min	2,644	0.34	7.28	11.2%	32.7%	22.1%	34.1%	34,517
	9-min	2,717	0.35	7.24	11.8%	32.9%	21.3%	34.0%	28,080
	11-min	2,836	0.36	7.15	10.6%	33.4%	21.0%	35.0%	41,058
Central	5-min	5,237	0.54	7.11	11.6%	24.9%	21.2%	42.4%	80,203
	7-min	5,316	0.55	7.15	13.1%	24.4%	21.8%	40.8%	76,913
	9-min	5,303	0.55	7.23	13.6%	25.2%	21.6%	39.7%	66,937
	11-min	5,556	0.58	7.23	12.5%	26.0%	22.2%	39.4%	78,881
West	5-min	3,173	0.46	6.98	7.4%	30.0%	27.5%	35.1%	53,155
	7-min	3,266	0.48	6.97	8.3%	30.2%	26.8%	34.7%	55,087
	9-min	3,264	0.48	7.03	8.4%	28.7%	26.9%	36.0%	45,854
	11-min	3,304	0.48	7.03	8.1%	29.1%	26.5%	36.3%	47,499

Table 33: Overview of Conflict Resolution Statistics for 2025 Scenarios

	Metric (No.) / Action Time	Number of Cfls. (1)	Conflict Density (2)	Avg. # Options per Cfl. (3)	Horz. Res. (4)	Direct-To Res. (5)	Vert. Res. (6)	Speed Res. (7)	Total Delay in minutes (8)
East	**5-min**	3,194	0.36	7.17	10.1%	35.4%	22.9%	31.6%	64,690
	7-min	3,283	0.37	7.14	10.7%	35.5%	22.4%	31.4%	59,641
	9-min	3,379	0.38	7.16	10.9%	34.6%	21.8%	32.8%	59,885
	11-min	3,441	0.39	7.18	10.1%	34.8%	21.2%	33.8%	64,599
Central	**5-min**	6,564	0.61	7.13	11.0%	26.8%	21.8%	40.4%	121,455
	7-min	6,652	0.62	7.12	11.7%	27.0%	22.1%	39.3%	115,830
	9-min	6,742	0.63	7.22	11.5%	27.5%	22.0%	39.1%	114,677
	11-min	6,848	0.64	7.17	11.3%	27.4%	22.2%	39.1%	105,703
West	**5-min**	4,306	0.56	6.71	7.5%	34.0%	26.8%	31.7%	106,159
	7-min	4,482	0.59	6.61	7.4%	35.2%	26.6%	30.8%	115,762
	9-min	4,410	0.58	6.70	7.5%	34.5%	26.3%	31.7%	110,405
	11-min	4,590	0.60	6.59	6.7%	34.6%	26.1%	32.6%	110,541

9. Appendix B

This appendix provides model description and parameter estimates for Model 3 presented in Section 3.2.2.2.4. Table 34 provides the expansion of Model 3's equation and Table 35 provides the 39 fitted coefficients of the model for each response variable. The later also includes the p-value for the estimated coefficient, indicating the statistical significance of that particular factor level on the response variable. Lastly, Figure 62 illustrates Model 3's residuals indicating that they are at least approximately normally distributed with zero means.

Table 34: Expansion of Model 3 Equation

Intercept & Main Effects:	$A0$ $+(j$=east, $A1$ or j=central, $A2$ or j= west, $A3) \times A_j$ $+ (i$=horizontal, $A4$ or i=direct-to, $A5$ or i=vertical, $A6$, or i=speed, $A7) \times M_i$ $+ A8 \times AT_k$ $+ A9 \times WT_l$
Two-way Interactions:	$+(j$=east & i=horizontal, $A10) \times A_j \times M_i$ $+(j$=east & i=direct-to, $A11) \times A_j \times M_i$ $+(j$=east & i=vertical, $A12) \times A_j \times M_i$ $+(j$=east & i=speed, $A13) \times A_j \times M_i$ $+(j$=central & i=horizontal, $A14) \times A_j \times M_i$ $+(j$=central & i=direct-to, $A15) \times A_j \times M_i$ $+(j$=central & i=vertical, $A16) \times A_j \times M_i$ $+(j$=central & i=speed, $A17) \times A_j \times M_i$ $+(j$=west & i=horizontal, $A18) \times A_j \times M_i$ $+(j$=west & i=direct-to, $A19) \times A_j \times M_i$ $+(j$=west & i=vertical, $A20) \times A_j \times M_i$ $+(j$=west & i=speed, $A21) \times A_j \times M_i$ $+(j$=east, $A22) \times A_j \times (AT_k - 8.01)$ $+(j$=central, $A23) \times A_j \times (AT_k - 8.01)$ $+(j$=west, $A24) \times A_j \times (AT_k - 8.01)$ $+(j$=east, $A25) \times A_j \times (WT_l - 6.30)$ $+(j$=central, $A26) \times A_j \times (WT_l - 6.30)$ $+(j$=west, $A27) \times A_j \times (WT_l - 6.30)$ $+(i$=horizontal, $A28) \times M_i \times (AT_k - 8.01)$ $+(i$=direct-to, $A29) \times M_i \times (AT_k - 8.01)$ $+(i$=vertical, $A30) \times M_i \times (AT_k - 8.01)$ $+(i$=speed, $A31) \times M_i \times (AT_k - 8.01)$ $+(i$=horizontal, $A32) \times M_i \times (WT_l - 6.30)$ $+(i$=direct-to, $A33) \times M_i \times (WT_l - 6.30)$ $+(i$=vertical, $A34) \times M_i \times (WT_l - 6.30)$ $+(i$=speed, $A35) \times M_i \times (WT_l - 6.30)$ $+A36 \times (AT_k - 8.01) \times (WT_l - 6.30)$
Squared Terms:	$+A37 \times (AT_k - 8.01)^2$ $+A38 \times (WT_l - 6.30)^2$

Table 35: Model 3 Parameter Estimates for Response Variables

Code	Term	% FB Impact		% FD Impact		% FT Impact		Maneuver Delay (s)	
		Estimate	P-Value	Estimate	P-Value	Estimate	P-Value	Estimate	P-Value
A0	Intercept	-0.060912	0.4970	0.0553224	0.5649	0.06109	0.5431	-3.856045	0.1727
A1	Airspace[East]	0.1609518	<.0001*	0.0283077	0.3253	0.0018065	0.9520	-3.941114	<.0001*
A2	Airspace[Central]	-0.073076	0.0072*	0.0627902	0.0308*	-0.001684	0.9555	3.5064177	<.0001*
A3	Airspace[West]	-0.087876	0.0014*	-0.091098	0.0019*	-0.000123	0.9968	0.4346967	0.6106
A4	Maneuver[Horizontal]	0.5325183	<.0001*	0.9999694	<.0001*	0.8207967	<.0001*	45.898926	<.0001*
A5	Maneuver[Direct-To]	-0.770282	<.0001*	-1.061663	<.0001*	-0.757083	<.0001*	-51.0652	<.0001*
A6	Maneuver[Vertical]	0.2900913	<.0001*	0.022537	0.5213	0.1504813	<.0001*	8.474529	<.0001*
A7	Maneuver[Speed]	-0.052328	0.1113	0.0391567	0.2656	-0.214195	<.0001*	-3.308257	0.0015*
A8	Action Time	0.01843	0.0305*	-0.011005	0.2263	-0.022715	0.0174*	-1.346569	<.0001*
A9	WarningTime	-0.008478	0.1547	0.0098176	0.1244	0.0129729	0.0524	1.2332542	<.0001*
A10	Airspace[East] × Maneuver[Horizontal]	0.1457725	0.0018*	0.369133	<.0001*	0.281189	<.0001*	10.517311	<.0001*
A11	Airspace[East] × Maneuver[Direct-To]	-0.409542	<.0001*	-0.31946	<.0001*	-0.248578	<.0001*	-7.952352	<.0001*
A12	Airspace[East] × Maneuver[Vertical]	0.4208485	<.0001*	-0.008713	0.8604	-0.034269	0.5082	-1.627625	0.2640
A13	Airspace[East] × Maneuver[Speed]	-0.157079	0.0008*	-0.04096	0.4087	0.0016577	0.9745	-0.937334	0.5196
A14	Airspace[Central] × Maneuver[Horizontal]	-0.155531	0.0009*	-0.287997	<.0001*	-0.214782	<.0001*	-9.11542	<.0001*
A15	Airspace[Central] × Maneuver[Direct-To]	0.3669774	<.0001*	0.4200341	<.0001*	0.2899784	<.0001*	11.72235	<.0001*
A16	Airspace[Central] × Maneuver[Vertical]	-0.375017	<.0001*	-0.097448	0.0507	0.0628851	0.2262	0.3240016	0.8241
A17	Airspace[Central] × Maneuver[Speed]	0.1635698	0.0005*	-0.03459	0.4862	-0.138082	0.0083*	-2.930931	0.0454*
A18	Airspace[West] × Maneuver[Horizontal]	0.009758	0.8334	-0.081136	0.1039	-0.066407	0.2022	-1.401891	0.3377
A19	Airspace[West] × Maneuver[Direct-To]	0.0425649	0.3827	-0.100574	0.0552	-0.041401	0.4484	-3.769998	0.0147*
A20	Airspace[West] × Maneuver[Vertical]	-0.045832	0.3238	0.1061602	0.0338*	-0.028616	0.5820	1.3036235	0.3726
A21	Airspace[West] × Maneuver[Speed]	-0.006491	0.8887	0.07555	0.1298	0.136424	0.0092*	3.8682657	0.0086*
A22	Airspace[East] × (Action Time-8.01)	-0.025634	0.0328*	-0.030158	0.0192*	-0.020572	0.1251	0.0938945	0.8028
A23	Airspace[Central] × (Action Time-8.01)	0.0053738	0.6531	0.0114299	0.3729	0.0115576	0.3885	-0.047617	0.8993
A24	Airspace[West] × (Action Time-8.01)	0.0202598	0.0934	0.0187281	0.1477	0.0090147	0.5040	-0.046277	0.9028
A25	Airspace[East] × (WarningTime-6.30)	0.0003836	0.9571	0.0104733	0.1717	0.0052905	0.5081	-0.483085	0.0324*
A26	Airspace[Central] × (WarningTime-6.30)	0.0132231	0.0672	-0.000564	0.9417	-0.005455	0.4988	-0.430243	0.0586
A27	Airspace[West] × (WarningTime-6.30)	-0.013607	0.0618	-0.009909	0.2034	0.000164	0.9839	0.9133277	<.0001*
A28	Maneuver[Horizontal] × (Action Time-8.01)	-0.013054	0.3720	0.0027593	0.8601	0.02019	0.2181	1.1098228	0.0166*
A29	Maneuver[Direct-To] × (Action Time-8.01)	-0.046469	0.0020*	-0.018934	0.2352	-0.008428	0.6126	-0.753461	0.1083
A30	Maneuver[Vertical] × (Action Time-8.01)	0.0709414	<.0001*	0.0099229	0.5265	-0.026768	0.1030	-1.277946	0.0059*
A31	Maneuver[Speed] × (Action Time-8.01)	-0.011418	0.4348	0.0062521	0.6898	0.0150069	0.3596	0.9215838	0.0461*
A32	Maneuver[Horizontal] × (WarningTime-6.30)	-0.005501	0.5275	-0.023778	0.0114*	-0.0383	0.0001*	-1.73408	<.0001*
A33	Maneuver[Direct-To] × (WarningTime-6.30)	0.0574577	<.0001*	0.0466607	<.0001*	0.0299479	0.0041*	0.5367946	0.0653
A34	Maneuver[Vertical] × (WarningTime-6.30)	-0.088707	<.0001*	-0.014433	0.1229	0.0245689	0.0124*	1.5179878	<.0001*
A35	Maneuver[Speed] × (WarningTime-6.30)	0.0367506	<.0001*	-0.008449	0.3656	-0.016216	0.0974	-0.320702	0.2426
A36	(Action Time-8.01) × (WarningTime-6.30)	-0.002841	0.2079	3.9985e-5	0.9868	-0.002776	0.2717	-0.145115	0.0417*
A37	(Action Time-8.01)* × (Action Time-8.01)	-0.00274	0.5653	-0.000962	0.8505	-0.001428	0.7890	0.0481556	0.7481
A38	(WarningTime-6.30) × (WarningTime-6.30)	0.0013362	0.3679	-0.000891	0.5750	-0.000841	0.6128	0.0255849	0.5837

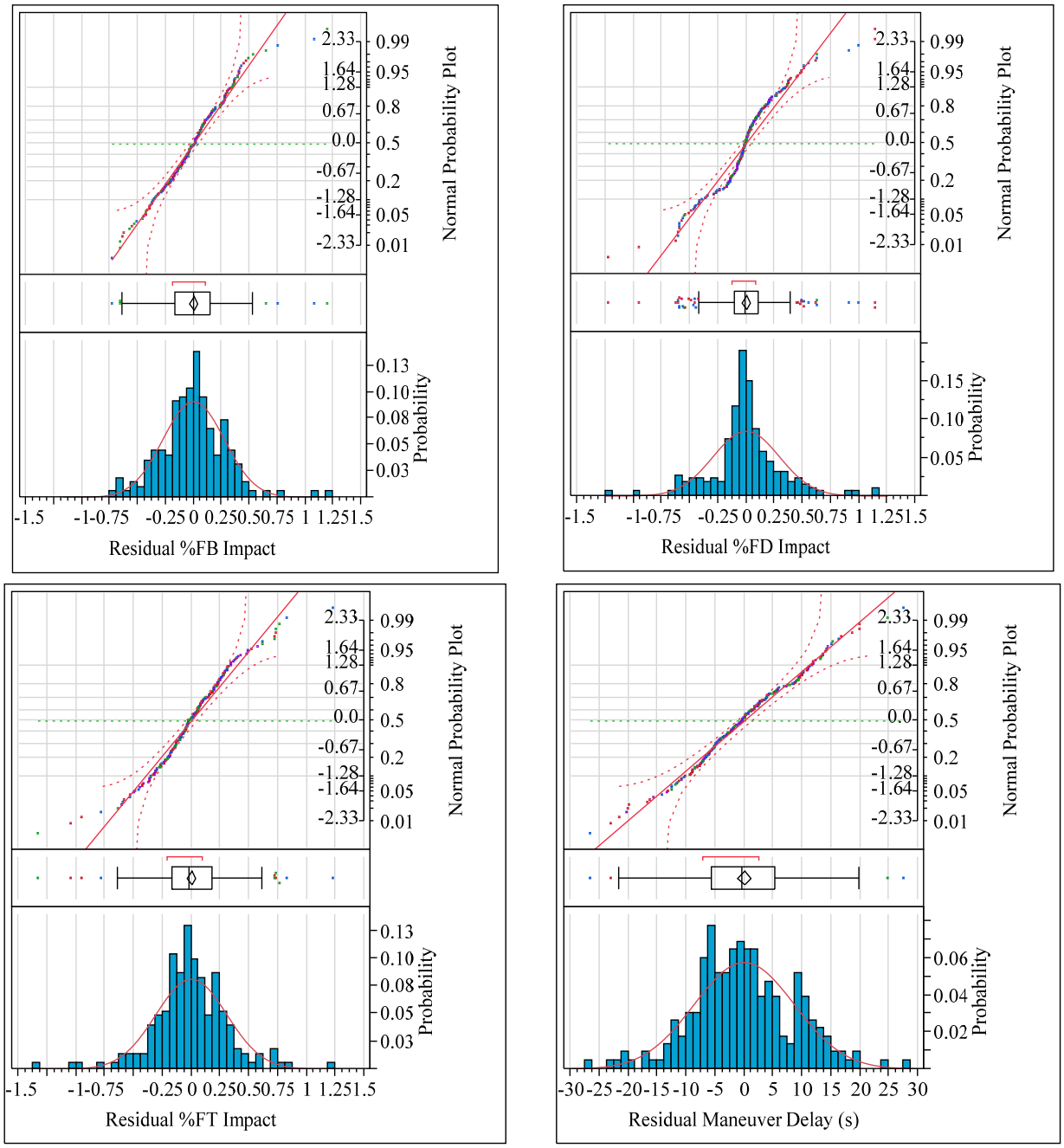

Figure 62: Residual Error Distributions for Responses from Model 3