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A Fuel-Efficient Conflict Resolution Maneuver for Separation Assurance

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Abstract

This experiment seeks to evaluate the benefit of augmenting a conflict detection and resolution algorithm to consider a fuel-efficient, Variable Speed Direct-To maneuver when resolving a given conflict based on either minimum fuel burn or minimum delay. Twelve conditions were tested in fast-time simulation conducted in three airspace regions with mixed aircraft types and nominal traffic. Inclusion of this maneuver had no appreciable effect on the ability of the algorithm to safely detect and resolve conflicts. Cumulative fuel-burn savings were significantly higher when selecting resolutions based on minimum fuel burn; average delay per resolution was only marginally higher.

1 Introduction

Air traffic demand is projected to double in the next 20 years (ref. 1). The human workload associated with conflict detection and resolution is expected to limit this increase and thereby limit the economic growth that aviation facilitates. Automated separation-assurance systems are proposed as a way to safely and efficiently separate aircraft in highly dense traffic situations up to two to three times current levels, thereby fostering increased economic growth for the nation.

Numerous algorithms have been proposed to provide separation assurance in the future air traffic system (ref. 2). Maintaining safe separation is the first-order objective of all such algorithms; the second-order objectives vary, but most of the proposed algorithms optimize the selection of conflict resolution maneuvers to minimize airborne delay in order to mitigate the effect on schedule. An alternative objective is to optimize based on fuel burn (refs. 2 and 3).

The Advanced Airspace Concepts (AAC) Autoresolver is strategic conflict resolution algorithm capable of deconflicting aircraft. AAC is a concept for automating separation assurance in the future that includes multiple layers of separation assurance for increased reliability. One component of AAC is the Autoresolver, a strategic problem-solving tool that is responsible for strategic separation assurance as well as weather avoidance and arrival metering, although for this study the focus is only on the separation-assurance function (refs. 4 and 5).

In reference 6, the system performance of a conflict resolution algorithm that selected resolutions based on minimum delay was compared to the system performance of the same algorithm when selecting resolutions based on minimum fuel burn. The most effective resolution maneuver when optimizing for airborne delay was a Direct-to maneuver, which identifies wind-favorable shortcuts along the planned route of an aircraft that reduce its flying time while resolving the predicted conflict (ref. 7). The most effective resolution maneuver when optimizing for fuel burn was a speed reduction maneuver, which employs a temporary speed reduction to resolve the predicted conflict. However, speed reductions were selected less frequently by the algorithm than other, lessfuel-efficient maneuvers. Additionally, when utilized, these maneuvers significantly increase the cumulative delay. It is hypothesized that the availability of a compound maneuver combining a Direct-To maneuver with the fuel efficiency of a speed reduction would improve the performance of the separation-assurance algorithm.

This study compares the system performance of a conflict resolution algorithm in realistic traffic scenarios with and without the availability of a compound Direct-to/speed-reduction maneuver, hereafter referred to as a Variable Speed Direct-To maneuver. The objective is to quantify the operational benefit of adding the proposed new maneuver to the set of maneuvers already available to the automated separation-assurance algorithm.

The next section describes the conflict resolution algorithm under test and the new compound maneuver. Then the experimental approach, procedure, and assumptions are discussed. The results are then categorized according to safety and efficiency. Lastly, a summary of the study findings is given, along with suggestions for future research.

2 Test Article

The conflict resolution algorithm evaluated in this study is the Advanced Airspace Concept (AAC) Autoresolver (refs. 4 and 5) . It is a ground-based algorithm that resolves conflicts in pairwise fashion and can be configured to select resolutions based on minimum delay or minimum fuel burn. The Autoresolver selects a maneuver from one of the following categories: horizontal, vertical, altitude, Direct-To, or compound. For this study, only conflicts with en-route flight maneuvers are analyzed; arrivals are not included because they adhere to additional constraints such as metering. In the following study only one compound maneuver is enabled: the Variable Speed Direct-To maneuver.

2.1 AAC Autoresolver

The AAC Autoresolver is a strategic conflict resolution algorithm designed to deconflict aircraft that are predicted to lose separation more than 2 minutes in the future. For aircraft en route, the look-ahead time is 8 minutes and up to 20 minutes for arriving aircraft. In this study, for every minute of simulation time the future trajectories of all aircraft are computed and processed to determine if there are any predicted losses of separation where two aircraft come within 5 nautical miles horizontally and 1,000 feet vertically of one another.

The Autoresolver receives a list of aircraft conflict pairs ordered by predicted time to first loss of separation. For each conflict in the conflict list, the Autoresolver follows an iterative approach for resolution. Accounting for characteristics such as aircraft type, speed, and airspace boundaries, the resolver calculates a future route composed of waypoints, speeds, and altitudes that may possibly resolve the conflict.

Figure 1 shows the types of future routes attempted by the Autoresolver, grouped by whether they are horizontal, vertical, or speed resolutions. This future route is then sent to a trajectory engine that computes a four-dimensional (4-D) trial resolution trajectory based on this route.

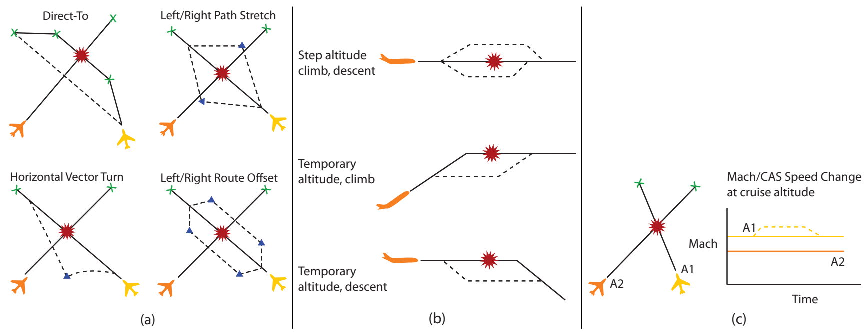

Figure 1: Resolution trajectories of type horizontal (a), vertical (b), and speed (c).

In order for the resolution to be viable, it must resolve the primary conflict and be free of predicted losses of separation with the primary aircraft in the conflictas well as any other aircraft in the airspacefor a specified period of time. If these conditions are met, the Autoresolver has successfully generated a candidate resolution trajectory and stores it. If the resolution is not free of primary or secondary conflicts, the Autoresolver computes a new resolution route and checks to determine if it is successful. For each resolution type this iteration is continued until a successful resolution is found or all possibilities of that type have been exhausted. For each successful resolution, both the associated delay and the fuel burn are calculated. A common spatial point on the original trajectory and the resolution trajectory is found. To calculate the delay, the time on the original trajectory at the common point is subtracted from the time on the resolution trajectory at the common point. Similarly for the fuel burn, the weight of the aircraft at the common point on the resolution trajectory is subtracted from the aircraft weight at that point, after the aircraft has flown the original trajectory. Figure 2 shows an example trajectory with a resolution maneuver represented by segments 3a and 3b. The algorithm evaluates the cost of segments 1, 2, and 3 versus the cost of segments 1, 2, 3a, and 3b.

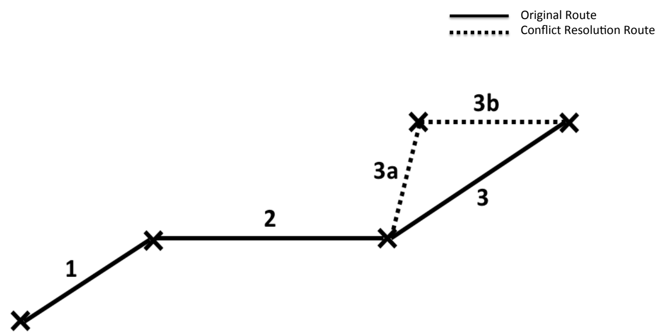

Figure 2: Delay and fuel burn estimation.

A discussion of how the aircraft weight is calculated and converted to fuel burn is given in a subsequent section. The resolver will generate up to 18 successful resolutions per aircraft in conflict for a maximum of 36 candidate resolution maneuvers between the two aircraft. In this study, the algorithm selects a resolution from among the set of successful resolutions using either the minimum delay or the minimum fuel-burn criterion, depending on how the algorithm is configured. The selected resolution is then implemented via fast-time, closed-loop simulation as discussed in the following sections. Further discussion regarding the design of the algorithm and the types of resolutions that are generated is presented in references 4 and 5 .

2.2 Variable Speed Direct-To Maneuver

The Autoresolver was modified to allow for the combination of a Direct-To maneuver with a reduction in speed. The reduced speed is chosen to exactly negate the time savings normally associated with a Direct-To maneuver; this reduction in speed produces a fuel-burn benefit while maintaining the flight-plan schedule. This compound maneuver is referred to as a Variable Speed Direct-To maneuver. A Direct-To maneuver resolves a conflict by taking an aircraft directly to a downstream waypoint, thus bypassing a dogleg in the flight plan. This modification augmented the existing Direct-To maneuver, thus allowing the algorithm to continue to have the option to utilize a Direct-To maneuver when efficient. The equation that describes a Direct-To maneuver is shown in reference 1, where Δt [[need to fix all these symbol callouts]] represents delay in hours, D_1 is the previous distance along the route in nautical miles, D_2 is the new distance in nautical miles, and S is speed in knots:

$$\Delta t = \frac{D_1}{S} - \frac{D_2}{S} \quad (1)$$

Augmenting equation (1) to produce a maneuver that results in zero delay requires setting d to zero, yielding equation (2), where S_{new} represents the new (slower) speed in order to result in a Variable Speed Direct-To maneuver. The algorithm abides by the original Direct-To constraints where the maneuver will not be considered if:

- the aircraft is less than 20 minutes from the arrival fix,
- the aircraft cannot return to the route within 50 n. mi. of the final fix,
- the path of the aircraft along the Direct-To route is greater than 250 n. mi. (dotted line in fig. 1(a)), and
- the point where the aircraft rejoins the trajectory is within 50 n. mi. of the current Air Route Traffic Control Center boundary.

In addition, it will not attempt to execute the maneuver if S_{new} is within 5 knots of the original speed.

$$S_{new} = (\frac{D_2}{D_1})S \quad (2)$$

For example, a Variable Speed Direct-To maneuver by an aircraft traveling 450 knots that will reduce the distance along the route from 400 to 360 n. mi. would reduce the speed to 405 (by 45) knots in order to produce no delay. When performing a Variable Speed Direct-To maneuver, the intent is for the aircraft to recapture the route at the same time it would have if it had not performed the maneuver. Figure 3 illustrates the Variable Speed Direct-To maneuver where A1 and A2 are aircraft predicted to conflict. To avoid this conflict, A1 is selected to execute a Variable Speed Direct-To maneuver. The new trajectory for A1 (dashed line) removes several waypoints and reduces the speed as shown in the neighboring profile. The Mach number of A1 is decreased for the duration of the maneuver and eventually returns to its original speed after clearing the conflict.

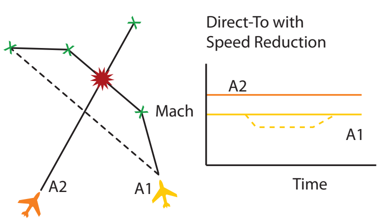

Figure 3: Variable Speed Direct-To maneuver.

3 Experiment Design

This section describes the simulation approach and the metrics used.

3.1 Simulation Environment

The Advanced Concepts Evaluations System (ACES) is a fast-time, agent-based simulation of the National Airspace System (NAS) that uses four-degree-of-freedom equations based on the Base of Aircraft Data (BADA) to generate aircraft trajectories (ref. 8). ACES was developed specifically to provide a general-purpose environment for evaluating future air traffic management and control concepts, including automated resolution algorithms. Essential to the simulation of resolution algorithms is the ability to generate 4-D trajectories. In ACES these trajectories begin at the departure fix and end at the arrival fix. By using aircraft-type-specific performance data together with guidance and navigation models, the ACES trajectory engine can generate representative trajectories for many aircraft. In the ACES simulation environment these aircraft trajectories are entirely deterministic; aircraft conflicts can be predicted with perfect accuracy, and resolution trajectories are guaranteed to be followed precisely by the simulated aircraft. In addition to deterministic aircraft trajectories, simplifications were made in the modeling and execution of the experiment. Negotiations of resolution trajectories between aircraft operators and/or the air navigation service provider were not modeled, nor were data-link transmission delays or pilot-action delays. Once a resolution trajectory was determined by the automation, it was executed immediately and precisely.

3.2 Simulated Airspace

In this study, the Autoresolver resolved conflicts in three pairs of adjacent Air Route Traffic Control Centers (ARTCCs). Each of the airspaces was simulated independently of each other and was selected based on its operational conflict properties as defined in reference 9. These properties fall into three categories that characterize the conflict, its relationship between two or more conflicts, and the locations of the conflicts within the NAS. In this study statistical clustering analysis was employed to categorize ARTCCs based on normalized conflict properties. As a result, three ARTCC pairs: Oakland-Los Angeles (ZOA-ZLA), Indianapolis-Chicago (ZID-ZAU), and Boston-New York (ZBW-ZNY) were identified that provided a wide representation of conflict properties. In order to create three distinct NAS regions, an adjacent center was chosen for each pair, creating (ZOA-ZLA) as representative of West Coast air traffic flow, (ZAU-ZID) as representative of Midwest air traffic flow, and (ZBW-ZNY) as representative of East Coast air traffic flow. By using the clusters shown in figure 4, we can model behavior seen over the entire

NAS, thus allowing a more complete assessment of the performance of the algorithm.

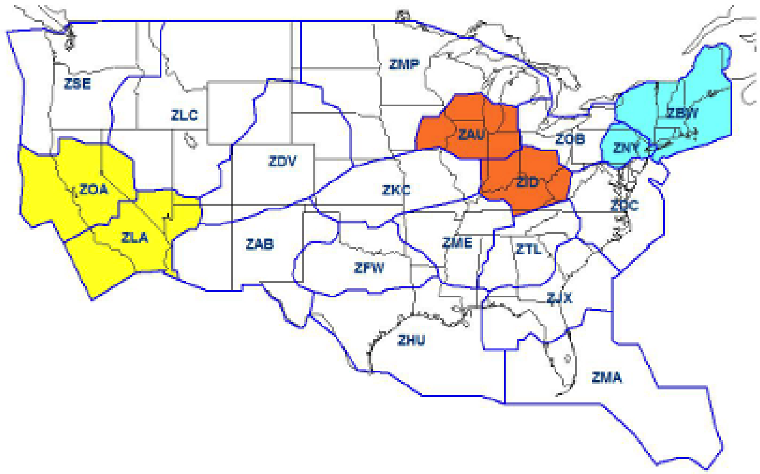

Figure 4: The ARTCCs simulated in this study.

3.3 Demand Set

Flight operations over a 24-hour period were simulated based on Aircraft Situation Display to Industry (ASDI) data recorded March 8, 2007. ASDI data come from the Federal Aviation Administrations (FAA's) Enhanced Traffic Management System (ETMS) and contain information about flights controlled by air traffic control. The dataset included 62,970 flights, their associated routes, and their departure times. This dataset had mixed aircraft types representing the current fleet mix. The data used in this study represent reasonable daily traffic in the NAS. The Rapid Update Cycle wind data were used to model winds in the selected ARTCCs (ref. 10). Figure 5 shows the conflict types represented within the demand set by ARTCC. Figure 5 illustrates a diversity of traffic flow types, with the East Coast containing primarily transitioning traffic, the Midwest predominately cruising traffic, and the West Coast a mix of all traffic types. The conflicts are coded as follows:

- CL/CL - Both aircraft are climbing.
- CL/CR- One aircraft is climbing while the other is cruising.
- CL/DE - One aircraft is climbing while the other is descending.
- CR/CR- Both aircraft are cruising.
- CR/DE - One aircraft is cruising while the other is descending.
- DE/DE- Both aircraft are descending.

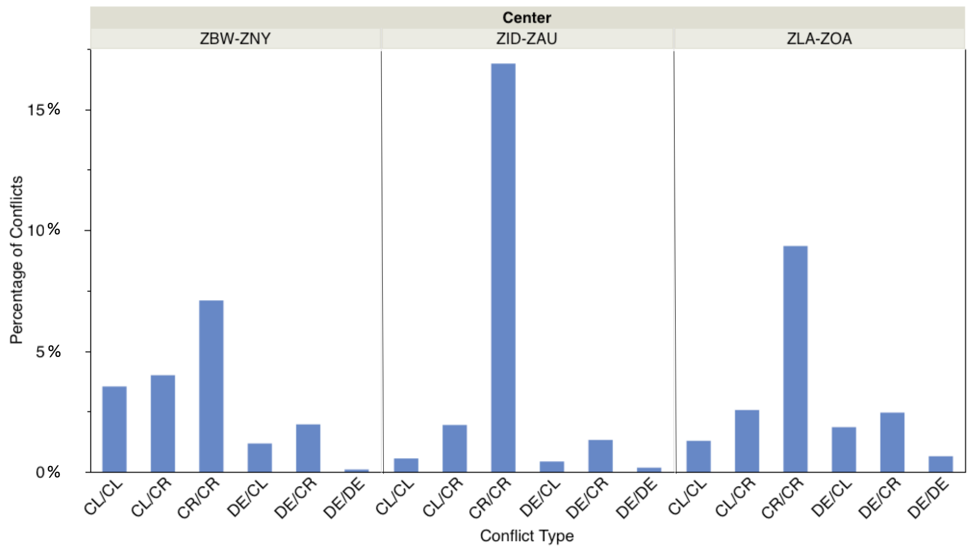

Figure 5: Conflict types per center.

3.4 Independent Variables

To evaluate the difference between the current state-of-the-art conflict resolution algorithm and the addition of a Variable Speed Direct-To maneuver, a test plan was developed that examines the behavior of the algorithm with and without this maneuver enabled in three pairs of ARTCCs under two conflict resolution optimization schemes. Table 1 shows the independent variables and settings. Each of the possible permutations is representative of a simulation run.

TABLE 1.- INDEPENDENT VARIABLES

Table 1. INDEPENDENT VARIABLES.

Independent Variables	Settings
Variable Speed Direct-To Maneuver	Enabled, Disabled
Optimization	Delay, Fuel Burn
Airspace	ZID-ZAU, ZBW-ZNY, ZOA-ZLA

3.5 Dependent Variables

The dependent variables for the experiment were the number of conflicts and the airborne delay and fuel burn incurred by flying the conflict resolution trajectories. In the development of a robust, efficient algorithm for implementation in the Next-Generation Air Transportation System (NextGen), safety is of the utmost concern. The number of conflicts is the metric used here to reflect the safety of the system. Efficiency in terms of delay and fuel burn is important once safety is assured. The fuel consumed per resolution is computed by ACES using aircraft-specific coefficients selected from the BADA (ref. 8). The BADA comprises the performance and operating procedure coefficients of 295 aircraft types. These coefficients encompass those that are used to calculate thrust, drag, and fuel flow along with those used to specify nominal cruise, climb, and descent speeds. Further discussion of the specific equations used to calculate the fuel burn is included in references 6 and 8. Evaluating the number of conflicts per simulation provides insight into the impact of the modifications made to the algorithm. A significant increase in the number of conflicts as a result of the availability of the Variable Speed Direct-To maneuver suggests increased risk. The safety- and efficiency-related results are presented in the section Results.

4 Results

This experiment seeks to evaluate the benefit of augmenting the AAC Autoresolver to consider a Variable Speed Direct-To maneuver when resolving a given conflict. The subsequent results address the safety and efficiency of potential implementation.

4.1 Safety

The primary safety metric for the experiment is the number of conflicts. A conflict occurs when aircraft are predicted to come within 5 n. mi. horizontally and 1,000 feet vertically from each other in en-route airspace. As expected, the addition of the Variable Speed Direct-To maneuver did not adversely affect the safety of the system, as measured by the total number of predicted conflicts. Figure 6 shows that in none of the test airspaces did the number of conflicts significantly increase when the Variable Speed Direct-To maneuver was enabled. On average, the percent difference between the baseline number of conflicts and the Variable Speed Direct-Toenabled scenario is less than 1%, suggesting that the inclusion of this maneuver does not adversely affect the ability of the algorithm to resolve conflicts, and there are no major gaps in its implementation.

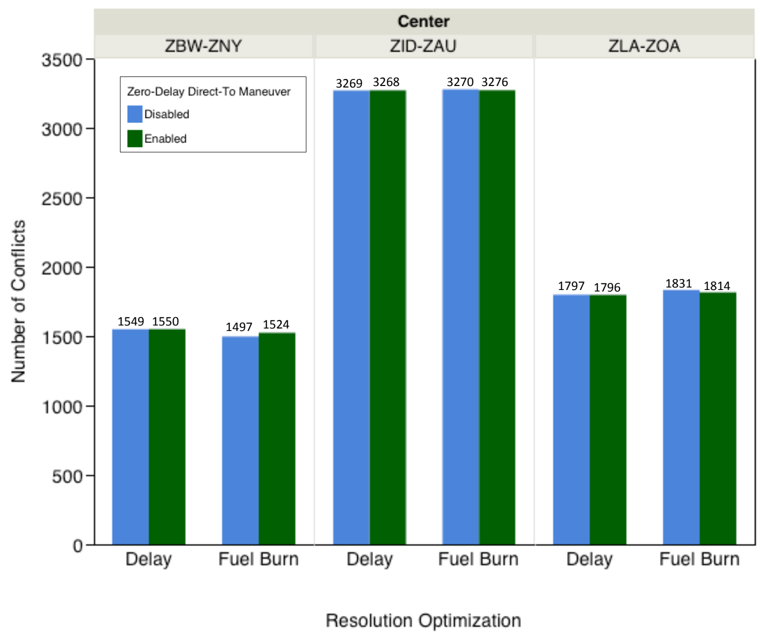

Figure 6: Number of conflicts.

4.2 Efficiency

4.2.1 Fuel Burn

When a Variable Speed Direct-To maneuver is executed, the maneuvered aircraft is slowed by an amount such that it will traverse its now, shorter Direct-To route in the same amount of time that it planned to traverse its original route. Figure 7 shows the distribution of speed-reduction magnitudes for ZID-ZAU. Seventy-five percent of all speed reductions observed in the experiment were less than 30 knots. A typical Boeing 737 aircraft at 35,000 feet will cruise between Mach 0.72 (415 knots) and Mach 0.76 (438 knots), approximately a 30-knot variation, indicating that most of the speed-reduction values required to obtain the desired fuel benefit are reasonable. Within our simulation, the range observed adhered to aircraft performance limitations. The speed-reduction ranges vs. the number of Variable Speed Direct-To maneuvers for the selected airspaces are shown in appendix A.

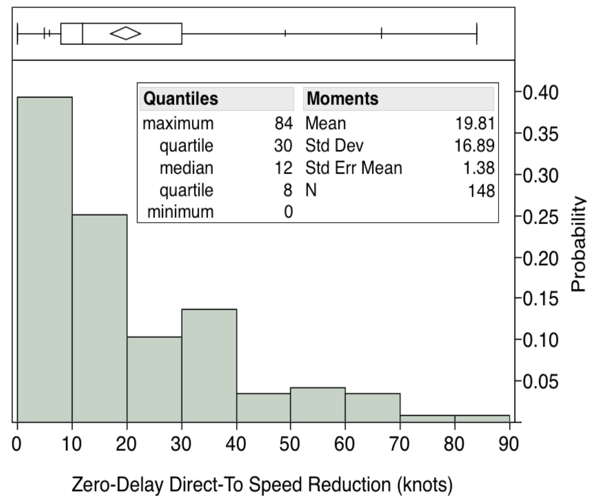

Figure 7: Variable Speed Direct-Toenabled speed reduction for ZID-ZAU; fuel burn optimal.

To evaluate the fuel burn associated with a resolution maneuver, the weight of the aircraft at the termination point on the resolution trajectory (where the aircraft rejoins the original trajectory) is subtracted from the aircraft weight at the same point, after the aircraft has flown the original trajectory.

Fuel-burn savings were higher by 92% in ZID-ZAU, 55% in ZBW-ZNY, and 47% in ZLA-ZOA when resolving conflicts with the Variable Speed Direct-To maneuver enabled.

Figure 8 shows the average fuel burn per resolution for the selected airspaces. The negative fuel burn seen in ZBW-ZNY and ZID-ZAU is an indication that the modification made to the algorithm causes it to outperform the nominal case when selecting resolutions based on minimum fuel burn. The average fuel burn per resolution in ZID-ZAU is 4.01 pounds less than when selecting resolutions based on minimum fuel burn with Variable Speed Direct-To maneuvers enabled. Similarly, in ZBW-ZNY the average fuel burn per resolution is 7.04 when optimizing for fuel burn with the maneuver enabled, a 2.43pound-per-resolution decrease. In ZLA-ZOA the average fuel burn per resolution is 2.73 pounds, 2.41 pounds less than when Variable Speed Direct-To is disabled.

Though these numbers are small, they are not insignificant when extrapolated to potential savings per year. In this study there were 3,276 conflicts in ZID-ZAU over the course of the day. Each of these conflicts requires one of the two aircraft to be maneuvered. Considering the average fuel savings of 4 pounds per resolution in ZID-ZAU, this savings amounts to roughly 4.8 million pounds of fuel per yearenough fuel to fill the tank of a Boeing 737-700 approximately 100 times. Furthermore, 20 ARTCCs within the continental United States could benefit from these savings.

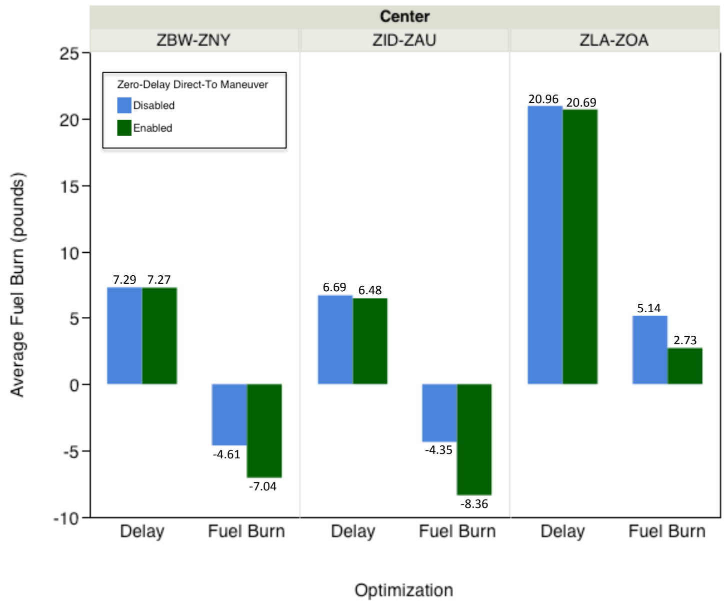

Figure 8: Average fuel burn.

Variation in traffic density and route length accounts for most of the difference in the magnitude of savings between the centers. ZID-ZAU center executed nearly twice as many resolution maneuvers as ZLA-ZOA and ZBW-ZNY, suggesting that the fuel efficiency of the resolutions the algorithm selects increases with the air traffic demand. However, the improvement seen in the delay cases is not as significant. When selecting resolutions based on delay, the algorithm finds Direct-To maneuvers to be more efficient. This increase in efficiency can be attributed to the fact that the selection of a Direct-To maneuver can result in negative delay and thus a time savings, whereas the most time-efficient zero-delay solution is zero and will not yield a time savings.

Figure 9 shows the resolutions selected by the algorithm for ZID-ZAU for fuel-burn optimization with Variable Speed Direct-To maneuvers enabled and disabled. Overall, the number of resolutions other than Direct-To or Variable Speed Direct-To remains consistent between scenarios. When Variable Speed Direct-To maneuvers were disabled, 306 Direct-To maneuvers were executed. When enabled, 181 Direct-To and 147 Variable Speed Direct-To maneuvers were executed, representing a 41% decrease in the number of Direct-To maneuvers.

When optimizing for minimum fuel burn, the algorithm frequently selected Variable Speed Direct-To maneuvers over traditional Direct-To maneuvers. However, in a small number of cases, a Direct-To maneuver was selected despite the fact that a Variable Speed Direct-To maneuver was available. In these instances, the additional fuel savings did not outweigh a decrease in flight time. The maneuver types for delay and fuel-burn optimization for each of the ARTCCs are shown in appendix B.

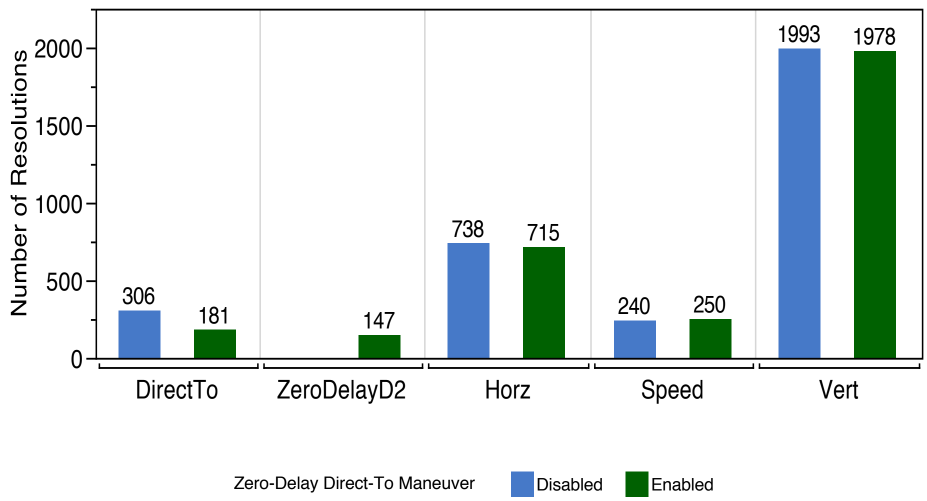

Figure 9: Resolution types in ZID-ZAU when optimizing for fuel burn.

4.2.2 Delay

Airborne delay is defined as the difference in time between the arrival time of an aircraft as given in the flight schedule and its actual arrival time. Although there are many sources of delay (e.g., air traffic control, weather, maintenance, crew availability), in the following analysis the source of delay is attributed to time difference between the modified trajectory and original trajectory of an aircraft at a common point in the en-route airspace. Positive delay occurs when the modified trajectory incurs additional flight time to avoid a loss of separation, akin to a detour. Negative delay is a reduction in flight time that can occur when a dogleg in the flight plan is eliminated or more favorable winds are encountered.

As expected, the inclusion of a Variable Speed Direct-To maneuver has almost no impact on delay when selecting resolutions based on delay. Figure 10 shows the average delay per resolution. When selecting resolutions based on minimum fuel burn, the average delay per resolution with the Variable Speed Direct-To maneuver enabled for ZID-ZAU is 10.86 seconds. For ZLA-ZOA under the same conditions, the average delay is 16.84 seconds, and it is 11.08 seconds for ZBW-ZNY. This delay translates to a 20% increase in cumulative delay in ZID-ZAU, but the absolute difference is only 4.7 minutes. Likewise, in ZLA-ZOA and ZBW-ZNY the difference is less than 1% when selecting resolutions based on delay. This finding supports the initial assertion that cumulative delay would only marginally increase with the availability of the Variable Speed Direct-To maneuver when resolution trajectories are optimized for airborne delay.

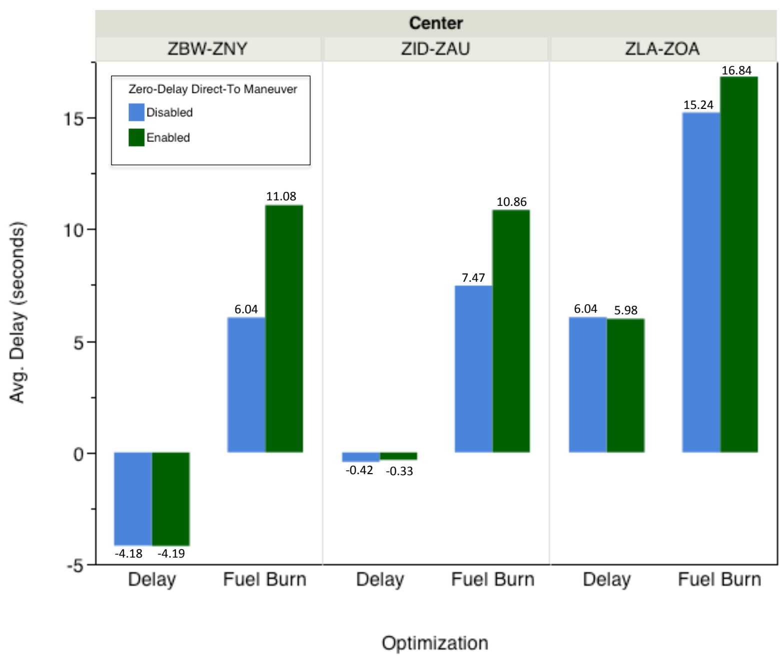

Figure 10: Average delay

Selecting resolutions based on minimum fuel burn with the Variable Speed Direct-To maneuver available increased the cumulative delay by 86% in ZBW-ZNY, 45% in ZID-ZAU, and 10% in ZLA-ZOA. The increase in cumulative delay is caused by the selection of fewer Direct-To maneuvers because of the fact that Variable Speed Direct-To maneuvers are more optimal than Direct-To maneuvers when optimizing for minimum fuel burn. There is a greater negative effect in ZBW-ZNY and ZID-ZAU when compared to ZLA-ZOA because the traffic in the first two cases had a greater number of Direct-To maneuvers that were no longer implemented. This finding is further discussed in relation to

ZID-ZAU in the next section.

Selecting resolutions based on minimum fuel burn increases the cumulative delay in each center. Figure 11 shows the cumulative delay per center for each optimization. This effect can be attributed to the selection of Variable Speed Direct-To maneuvers to resolve the associated conflict. As opposed to Direct-To maneuvers that can potentially yield a time savings, these maneuvers result in zero delay benefit. Additionally, when optimizing for fuel burn, the algorithm prefers speed-reduction maneuvers that tend to increase delay within the system. Each implementation of Variable Speed Direct-To changes the way the primary and, consequently, secondary conflicts are solved. Because only one aircraft of the pair will be maneuvered to avoid a conflict, the average delay per resolution can be thought of as per aircraft.

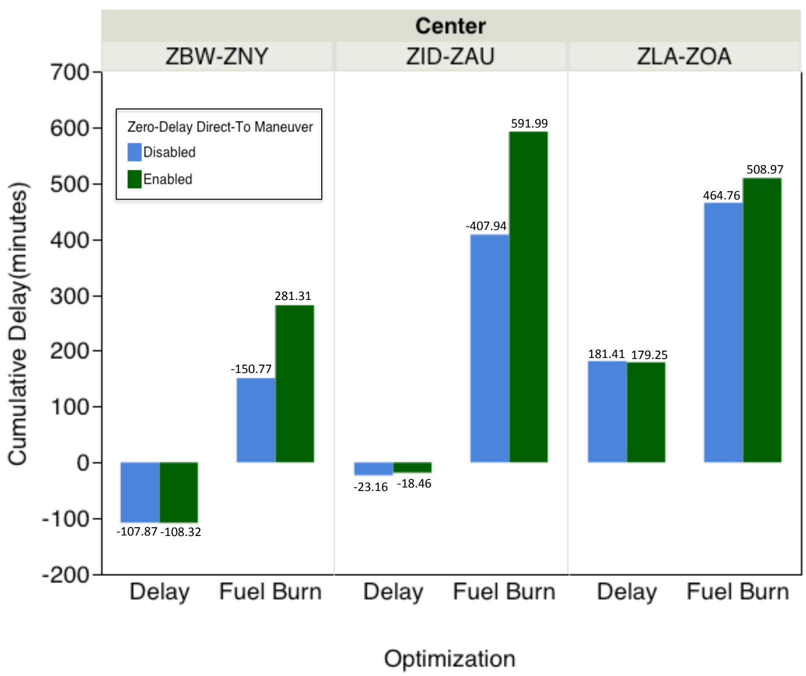

Figure 11: Cumulative delay

Generally, increasing the delay is considered to be undesirable. However, there are strategic instances in which this increase could be of value, such as an aircraft that needs to be slowed in order to meet the requested time of arrival. The magnitude of additional delay per resolution is small when compared to the 15-minute FAA definition of a reportable delay (ref. 11). The largest amount of delay per resolution observed when optimizing for fuel burn utilizing the Variable Speed Direct-To maneuver was 4 minutes. Even if marginal, the system-wide effects of an increase in delay are difficult to determine.

5 Conclusions

Twelve conditions were simulated to evaluate the benefit of modifying the AAC Autoresolver to consider a Variable Speed Direct-To maneuver when resolving a given conflict. Two methods of resolution selection were used: minimum delay and minimum fuel burn. The experiment was conducted in a fast-time environment using data representing a reasonable traffic day in the NAS.

The results showed that augmenting the existing algorithm to include the compound maneuver did not significantly influence the ability of the algorithm to resolve conflicts, nor did it affect the number of conflicts observed.

The inclusion of Variable Speed Direct-To increased the cumulative fuel-burn savings by 92% in ZID-ZAU, 55% in ZBW-ZNY, and 47% in ZLA-ZOA when selecting resolutions based on minimum fuel burn. In these results, the average penalty in delay per aircraft was on the order of a few seconds. Further analysis is required to determine the effect of increasing the delay as well as the balance between delay and fuel-burn benefit.

The cumulative fuel-burn savings observed in this study suggests that the Variable Speed Direct-To maneuver could provide significant fuel savings with no significant effect on safety or schedule.

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Appendix A

A.0 A.0

This appendix includes supplemental plots for speed distribution, maneuver types, and distance from final fix.

When a Variable Speed Direct-To maneuver is executed, the maneuvered aircraft is slowed by an amount such that it will traverse its now, shorter Direct-To route in the same amount of time that it planned to traverse its original route. Figures A-1 through A-3 show the distribution of speed-reduction magnitudes for the simulated airspaces. The majority of all speed reductions observed in the experiment were less than 30 knots.

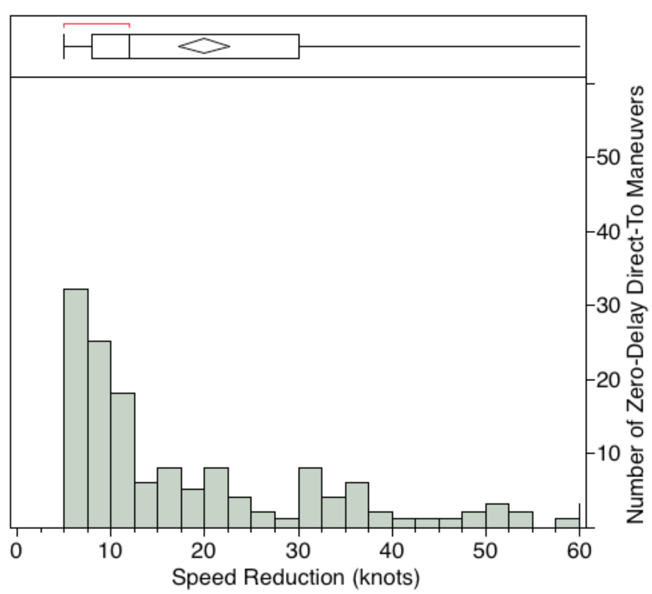

Figure A1: - Variable Speed Direct-Toenabled speed reduction, ZID-ZAU.

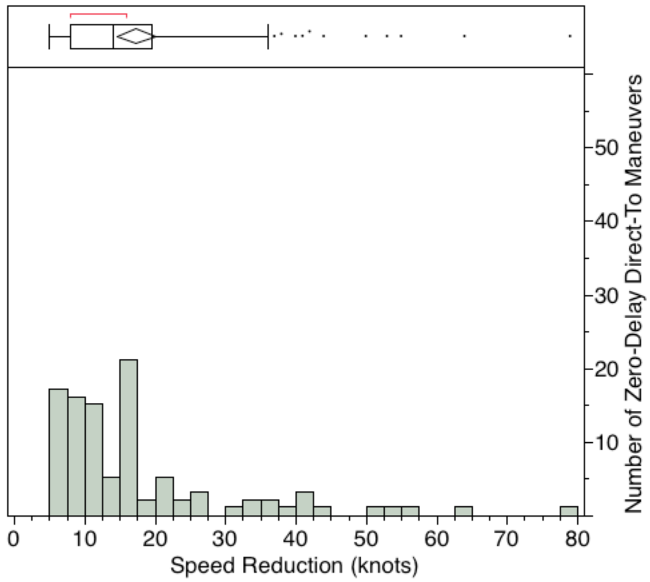

Figure A2: - Variable Speed Direct-Toenabled speed reduction, ZBW-ZNY.

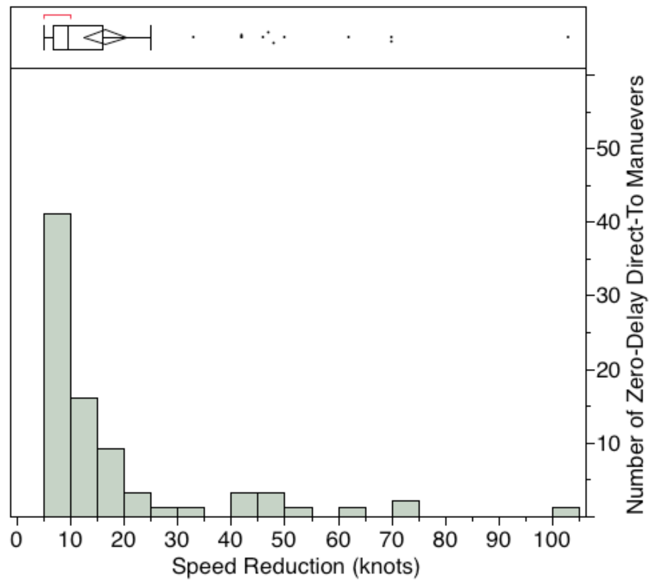

Figure A3: - Variable Speed Direct-Toenabled speed reduction, ZLA-ZOA

Appendix B

B.0 B.0

Figures B-1 and B-2 show the resolutions selected by the algorithm for the chosen airspaces for fuel-burn optimization with Variable Speed Direct-To maneuvers enabled and disabled.

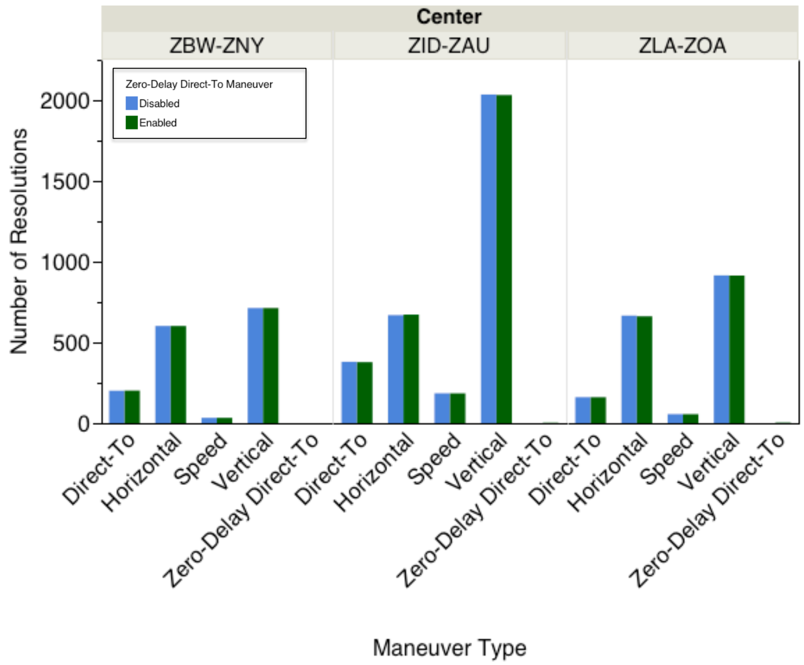

Figure B1: - Maneuver types for all centers, delay optimization.

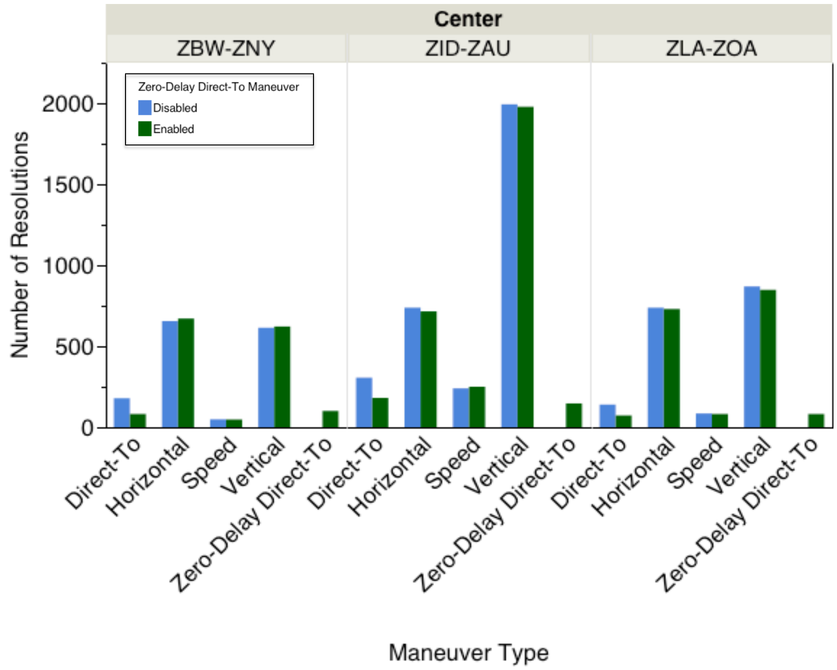

Figure B2: - Maneuver types for all centers, fuel-burn optimization.

When selecting resolutions based on delay, the algorithm finds Direct-To maneuvers to be more efficient than Variable Speed Direct-To maneuvers. This finding can be attributed to the fact that the selection of a Direct-To maneuver can result in negative delay and thus a time savings, whereas the most time-efficient zero-delay solution is zero and will not yield a time savings. The lack of Variable Speed Direct-To maneuvers selected in figure B-1 illustrates this point.

When selecting resolutions based on fuel burn, the number of Direct-To maneuvers selected decreases when compared to selecting resolutions based on delay. This finding can be attributed to the fact that the selection of Variable Speed Direct-To maneuvers can yield fuel savings greater than that of a Direct-To. The increase of Variable Speed Direct-To maneuvers selected in Figure B-2 compared to B-1 illustrates this point.

Appendix C

Figures C-1 through C-3 show the distance from the final fix in nautical miles when the maneuvered aircraft executed a Variable Speed

Direct-To maneuver. A significant number of the observed maneuvers are implemented within 1000 nautical miles of the final fix.

C.0

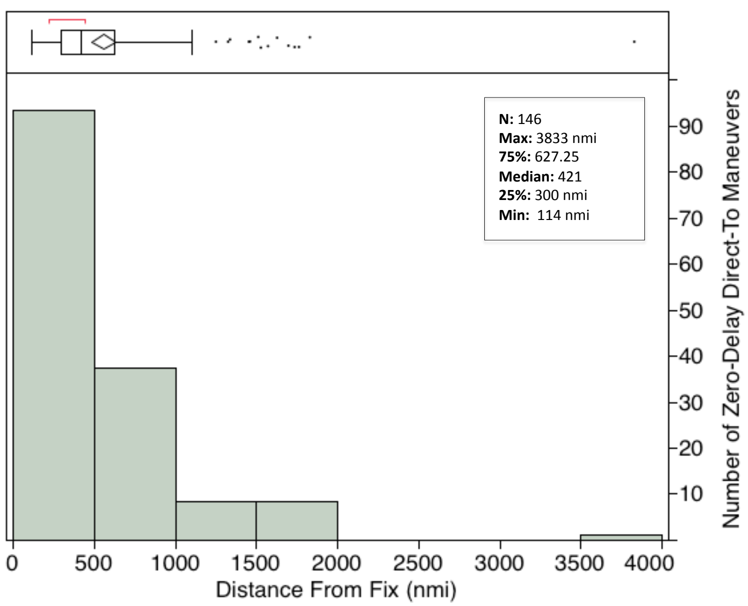

Figure C3: - Distance from fix, ZID-ZAU.

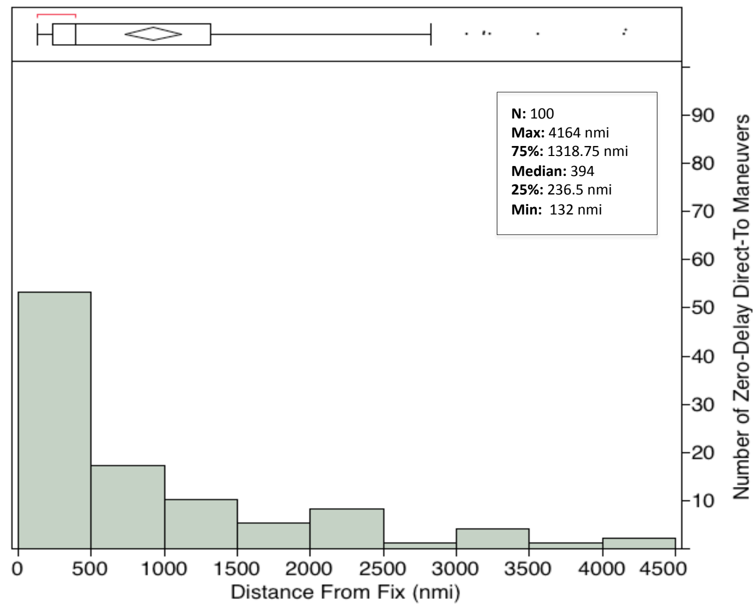

Figure C4: - Distance from fix, ZBW-ZNY.

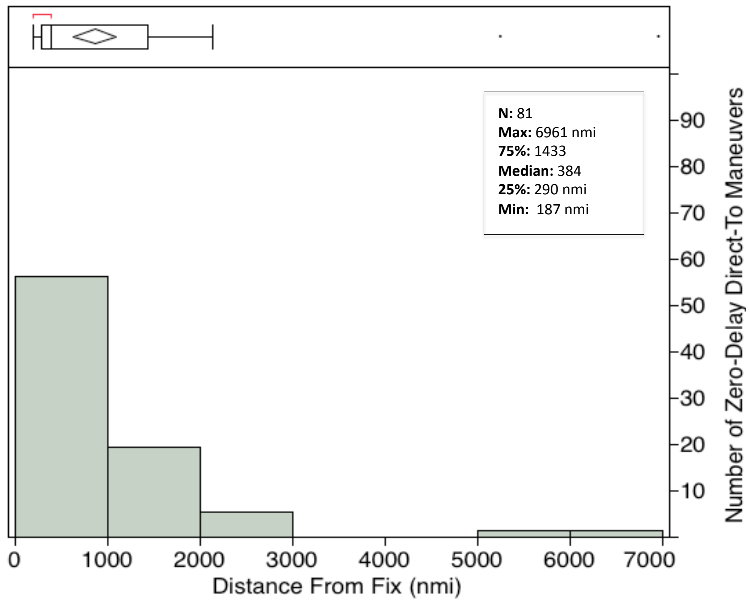

Figure C5: - Distance from fix, ZLA-ZOA.

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14. ABSTRACT
This experiment seeks to evaluate the benefit of augmenting a conflict detection and resolution algorithm to consider a fuel-efficient, Variable Speed Direct-To maneuver when resolving a given conflict based on either minimum fuel burn or minimum delay. Twelve conditions were tested in fast-time simulation conducted in three airspace regions with mixed aircraft types and nominal traffic. Inclusion of this maneuver had no appreciable effect on the ability of the algorithm to safely detect and resolve conflicts. Cumulative fuel-burn savings were significantly higher when selecting resolutions based on minimum fuel burn; average delay per resolution was only marginally higher.

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