Evaluation of a Fuel Efficient Aircraft Maneuver for Conflict Resolution

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Abstract - *Automated separation assurance algorithms are envisioned to play an integral role in accommodating the forecasted increase in demand of the National Airspace System. Developing a robust, reliable, air traffic management system involves safely increasing efficiency and throughput while considering the potential impact on users. This experiment seeks to evaluate the benefit of augmenting a conflict detection and resolution algorithm to consider a fuel efficient, Zero-Delay Direct-To maneuver, when resolving a given conflict based on either minimum fuel burn or minimum delay. A total of eight conditions were tested in a fast-time simulation conducted in two airspace regions with mixed aircraft types and light weather. Results show that inclusion of this maneuver has no appreciable effect on the ability of the algorithm to safely detect and resolve conflicts. The results further suggest that enabling the Zero-Delay Direct-To maneuver significantly increases the cumulative fuel burn savings when selecting resolution based on minimum fuel burn while marginally increasing the average delay per resolution.*

Keywords: Air traffic management, conflict detection and resolution, separation assurance, national airspace system.

1 Introduction

Air traffic demand is projected to increase significantly in the upcoming years [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 [2, 3]. Maintaining safe separation is the first-order objective of all such algorithms; the second-order objectives vary, however. The majority 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.

In [4] 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 an aircraft’s planned route that reduce its flying time while resolving the predicted conflict [5]. 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 than other, less fuel-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 Zero-Delay Direct-To maneuver. The objective is to quantify the operational benefit of adding the proposed maneuver to the set of maneuvers already available to the automated separation assurance algorithm.

This paper is organized as follows. Section 2 describes the conflict resolution algorithm under test and the new compound maneuver. Section 3 presents the experimental approach, procedure, and assumptions. The results are then categorized according to safety and efficiency. Lastly, a summary of the study’s 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 [6, 7]. It is a ground-based algorithm that resolves conflicts in pairwise fashion and can be optimized for airborne delay or for 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 where en route flights were maneuvered are analyzed; arrivals were not included because they adhere to additional constraints such as metering. In the following study only one compound maneuver is enabled: the Zero-Delay Direct-To maneuver.

2.1 Zero-Delay Direct-To Maneuver

The Autoresolver was modified to allow for the combination of a Direct-To maneuver with a reduction in speed. This compound maneuver is referred to as a Zero-Delay Direct-To maneuver. 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 (1) where d 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:

$$d = \frac{D_1}{S} - \frac{D_2}{S} \qquad (1)$$

Augmenting the above equation to produce a maneuver that results in zero delay requires setting d to zero. This yields equation 2 where S_{new} represents the new (slower) speed in order to result in a Zero-Delay Direct-To maneuver. The algorithm abides by the original Direct-To constraints where the maneuver will not be considered if the aircraft (1) is less than 20 minutes from the arrival fix, (2) cannot return to the route within 50 nmi of the final fix, (3) path along the Direct-To route is greater than 250 nmi (dotted line in Figure 1), and (4) if the point where the aircraft rejoins the trajectory is within 50 nmi 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.

$$S_{new} = \left(\frac{D_2}{D_1}\right) S \qquad (2)$$

For example, a Direct-To maneuver by an aircraft traveling 450 knots that will reduce the distance along the route from 400 to 360 nmi would reduce the speed to 405 (by 45) knots in order to produce no delay. When performing a Zero-Delay Direct-To maneuver, the aircraft would recapture the route at the same time it would had it not performed the maneuver. Figure 1 illustrates the Zero-Delay Direct-To maneuver where A_1 and A_2 are aircraft predicted to conflict. To avoid this, A_1 is selected to execute a Zero-Delay Direct-To maneuver. The new trajectory for A_1 (dashed line) removes several waypoints and reduces the speed as shown in the neighboring profile. The Mach number of A_1 decreases for the duration of the maneuver and eventually returns to its original speed after clearing the conflict.

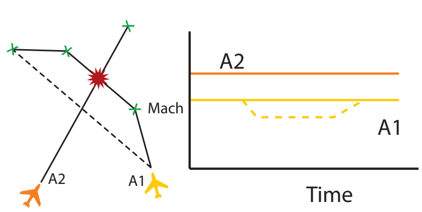

Figure 1. Zero-Delay Direct-To

2.2 Resolution Selection Criteria

The resolver will generate up to 18 successful resolutions per aircraft in conflict for a total of 36 available between the two aircraft. More specifically, the algorithm selects a successful resolution in each of the following categories for each aircraft:

- Vector Left
- Climb
- Speed Increase
- Direct-To
- Left Horizontal Vector Turn
- Vector Right
- Descend
- Speed Decrease
- Zero-Delay Direct-To
- Right Horizontal Vector Turn

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 experiment as discussed next. Further discussion regarding the design of the algorithm and the types of resolutions that are generated is presented in [7].

3 Experiment

3.1 Test Bed

The Airspace Concept Evaluation System (ACES) was used to simulate the National Airspace System (NAS) in a fast-time simulation [8]. ACES was also used to compute and archive the dependent variables: the number of losses of separation and the airborne delay and fuel burn incurred flying the conflict resolution trajectories.

3.2 Procedure

To evaluate the difference between the current state-of-the-art conflict resolution algorithm and the addition of a Zero-Delay Direct-To maneuver, a test plan was developed that examines the behavior of the algorithm with and without this maneuver enabled in two pairs of Air Route Traffic Control Centers (ARTCCs) under two conflict resolution optimization schemes. In [9], statistical clustering analysis was employed to categorize ARTCCs based on normalized conflict properties. The two ARTCC pairs selected for this experiment—Indianapolis (ZID) - Chicago (ZAU) and Los Angeles (ZLA) - Oakland (ZOA) —were chosen because they provide a wide representation of conflict properties. Table 1 shows the independent variables and settings.

Independent Variables	Settings
Zero-Delay Direct-To maneuver	Available, Unavailable
Optimization	Delay, Fuel Burn
Center	ZID-ZAU, ZLA-ZOA

Table 1. Independent Variables

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 comes from the FAA's Enhanced Traffic Management System (ETMS) and contains information about flights controlled by air traffic control. The data set 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 represents reasonable daily traffic in the NAS with a relatively small amount of weather induced delay. The Rapid Update Cycle wind data was used to model winds in the selected ARTCCs.

3.4 Dependent Variables

The dependent variables for the experiment were the number of losses of separation 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 losses of separation is the metric used here to reflect the safety of the system. Those results are presented in Section 4.1.

Efficiency in terms of delay and fuel burn are important once safety is assured. To calculate the delay imposed by executing a resolution maneuver, the time on the original trajectory at a common point is subtracted from the time on the resolution trajectory at the common point. Similarly, to estimate the fuel burn associated with a resolution maneuver, the weight of the aircraft at the common point for the resolution trajectory is subtracted from the aircraft weight for the original trajectory. The fuel consumed per resolution is computed by ACES using aircraft-specific coefficients selected from the Base of Aircraft Data (BADA) [10]. The BADA is comprised of 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 [4]. The efficiency-related results are presented in Section 4.2.

4 Results

This experiment seeks to evaluate the benefit of augmenting the Autoresolver to consider a Zero-Delay 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 losses of separation. A loss of separation occurs when aircraft are less than 5 nmi horizontally and 1,000 feet vertically from each other in en route airspace. As expected, the addition of the Zero-Delay Direct-To maneuver did not adversely affect the safety of the system, as measured by losses of separation.

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 Zero-Delay Direct-To maneuver might suggest increased risk. Figure 2 shows that enabling the compound maneuver does not significantly increase the number of conflicts in either ARTCC. On average, the percent difference between the baseline number of conflicts and the Zero-Delay Direct-To enabled scenario is less than 1%. This suggests 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.

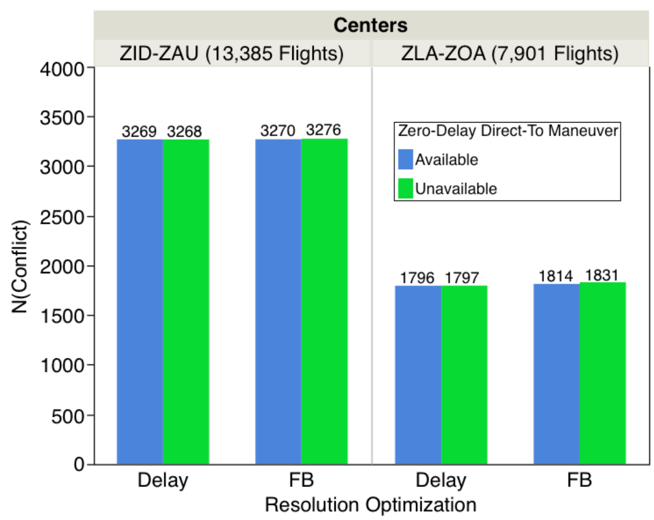

Figure 2. Number of Conflicts

4.2 Efficiency

The following section uses fuel burn and delay as a metric to evaluate the efficiency of the addition of the Zero-Delay Direct-To maneuver to the base algorithm. This is different than discussing delay and fuel burn as an optimizing factor because for each resolution implemented these metrics are computed. Although the algorithm is selecting resolutions based on fuel burn or delay, both the delay and fuel burn values per maneuver were tabulated, thus allowing for comparison.

4.2.1 En Route Delay Metric

Flight arrival delay is defined as the difference in time between the arrival time of an aircraft as given in the flight schedule and its real 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 aircraft's modified trajectory and original trajectory 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, much akin to a detour. Negative delay is a reduction in flight time that can occur when a dogleg in the flight is eliminated or more favorable winds are encountered.

The inclusion of Zero-Delay Direct-To maneuver has almost no impact on delay when selecting resolutions based on delay. Figure 3 shows the average delay per resolution. When selecting resolutions based on minimum fuel burn the average delay per resolution with the Zero-Delay 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. This translates to a 20.29% increase in cumulative delay in ZID-ZAU, but the absolute difference is only 4.7 minutes. Likewise, in ZLA-ZOA the difference is less than 1% when selecting resolutions based on delay. This supports the initial assertion that cumulative delay would only marginally increase with the availability of the Zero-Delay Direct-To maneuver when resolution trajectories are optimized for airborne delay.

Selecting resolutions based on minimum fuel burn with the Zero-Delay Direct-To maneuver available increased the cumulative delay by 45.12% in ZID-ZAU and 10.49% in ZLA-ZOA. The increase in cumulative delay is caused by the selection of fewer Direct-To's due to the fact that Zero-Delay Direct-To maneuvers are more optimal than Direct-To's when optimizing for minimum fuel burn. There is a greater negative effect in ZID-ZAU than ZLA-ZOA because the traffic in ZID-ZAU had a greater number of Direct-To's that were no longer implemented. This finding will be further discussed in the next section.

Selecting resolutions based on minimum fuel burn appears to result in an increase in cumulative delay in each center. This effect can be attributed to secondary conflicts. Each implementation of Zero-Delay 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.

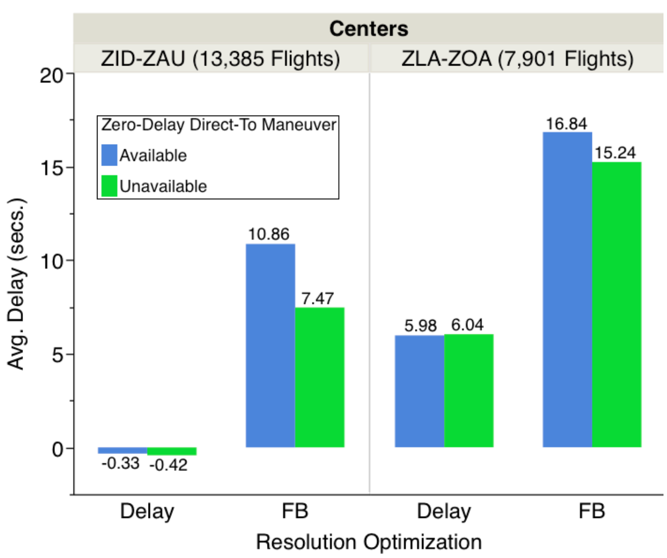

Figure 3. Average Delay

Generally, increasing the delay is considered to be undesirable. However, the magnitude of additional delay per resolution is small when compared to the 15-minute Federal Aviation Administration (FAA) definition of a "reportable" delay [11]. Even if marginal, the system-wide effects of an increase in delay are difficult to determine.

4.2.2 Fuel Burn Metric

When a Zero-Delay Direct-To maneuver is executed the maneuvered aircraft is slowed by a specified amount. Figure 4 shows the distribution of speed reduction magnitudes for ZID-ZAU. 75% of all speed reductions observed in the experiment were less than 30 knots. A typical Boeing 747-400 aircraft at 35,000 feet will cruise between Mach 0.8 (533 knots) and Mach .85 (566 knots) approximately a 30-knot variation. This indicates that the majority 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.

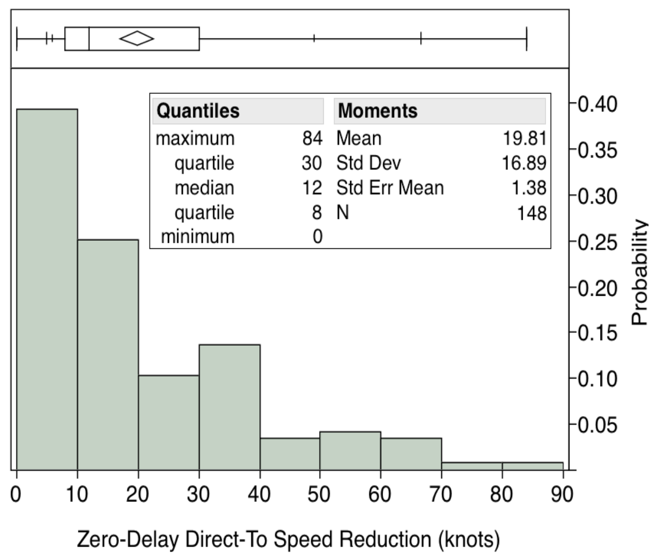

Figure 4. Zero-Delay Direct-To Enabled Speed Reduction ZID-ZAU Fuel Burn Optimal

To evaluate the fuel burn associated with a resolution maneuver, the weight of the aircraft at a common point on the resolution trajectory is subtracted from the aircraft weight for the original trajectory. The utilization of Zero-Delay Direct-To maneuvers increases the fuel burn savings by 91.85% in ZID-ZAU and by 47.48% in ZLA-ZOA when resolving conflicts. Figure 5 shows the average fuel burn per resolution for ZID-ZAU and ZLA-ZOA. The negative fuel burn seen in ZID-ZAU is an indication that the modification made to the algorithm causes it to outperform 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 Zero-Delay Direct-To maneuvers enabled. In ZLA-ZOA the average fuel burn per resolution is 2.73 pounds, this is 2.41 pounds less than when Zero-Delay Direct-To is disabled.

Though these numbers may seem insignificant the potential fuel benefit is great when considering the savings per year. In this study there were 3,276 conflicts in ZID-ZAU over the course of the day. Each of these requires one of the two aircraft to be maneuvered. Considering the average fuel savings of 4 pounds per resolution in ZID-ZAU, this amounts to roughly 4.8 million pounds of fuel per year. This is enough fuel to fill the tank of a Boeing 737-700 approximately 100 times. Furthermore, there are 20 ARTCCs within continental United States that could benefit from these savings.

Variation in traffic density and route length accounts for most of the difference in the magnitude of savings between the two centers. ZID-ZAU center executed nearly twice as many resolution maneuvers as ZLA-ZOA, suggesting that the fuel efficiency of the algorithm 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 can be attributed to the fact that the selection of a Direct-To can result in negative delay and thus a time saving whereas the most time-efficient Zero Delay solution is zero and will not yield a time savings. Figure 6 shows the resolutions selected by the algorithm for ZID-ZAU for fuel burn optimization with Zero-Delay Direct-To maneuvers enabled and disabled. Overall, the number of resolutions other than Direct-To or Zero-Delay Direct-To remains consistent between scenarios. When Zero-Delay Direct-To maneuvers were disabled there were 306 Direct-To's executed. When enabled there were 181 Direct-To's and 147 Zero-Delay Direct-To's. This represents a 41% decrease in the number of Direct-To maneuvers.

When optimizing for minimum fuel burn, the algorithm frequently selects Zero-Delay Direct-To maneuvers over traditional Direct-To maneuver. However, in a small number of cases, a Direct-To maneuver is selected despite the fact that a Zero-Delay Direct-To maneuver is available. In these instances, the additional fuel savings does not outweigh a decrease in flight time.

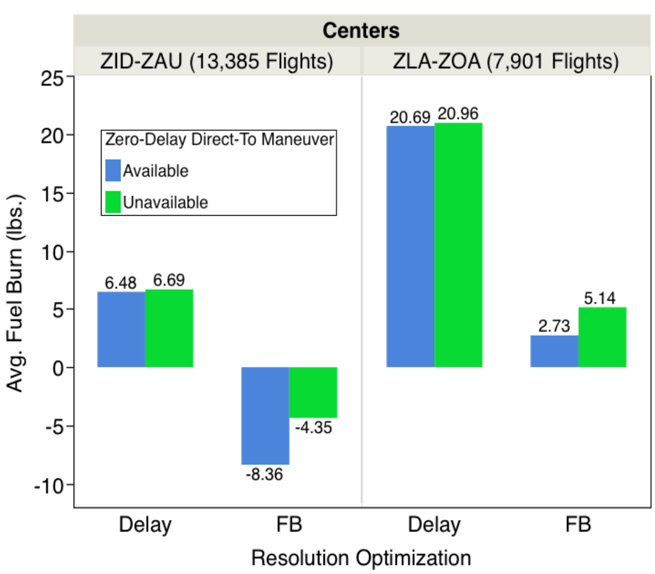

Figure 5. Average Fuel Burn

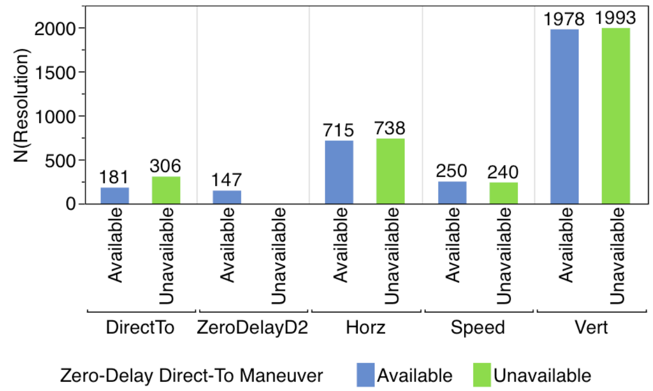

Figure 6. Resolution Types in ZID-ZAU when Optimizing for Fuel Burn

5 Conclusion

Eight conditions were simulated to evaluate the benefit of modifying the AAC Autoresolver to consider a Zero-Delay 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 algorithm's ability to resolve conflicts or effect the number of losses of separation observed.

The inclusion of Zero-Delay Direct-To increased the cumulative fuel burn savings by 91.85% in ZID-ZAU and 47.48% in ZLA-ZOA when selecting resolutions based on minimum fuel burn. In this scenario, the average penalty in delay per aircraft is on the order of 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 within this study suggests that the Zero-Delay Direct-To maneuver could provide significant fuel savings in future systems while maintaining safety and schedule.

6 Future Work

In en route airspace, aircraft operate within desired performance envelopes and operational speed limitations. To address these factors a survey concerned with evaluating the effects of distinct performance envelopes on the feasibility of the Zero-Delay Direct-To maneuver is planned. In addition, the operational soundness of the speed reduction distribution requires validation by subject matter experts. Furthermore, the prior work introduced the addition of a Zero-Delay Direct-To maneuver within the

Advanced Airspace Concept Autoresolver. The experiment then looked at the performance of the Zero-Delay Direct-To maneuver when selecting resolutions for either minimum fuel burn or minimum delay. This leaves a gap in coverage for a follow-on simulation to explore a hybrid selection scheme where resolution selection is based on a tradeoff between the two cost functions.

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References

[1] Federal Aviation Administration, "Terminal Area Forecast Summary, Fiscal Years 2010-2030", FAA HQ111308, 2010.

[2] Kuchar, J.K., Yang, L.C., " A Review of Conflict Detection and Resolution Modeling Methods", IEEE Transactions on Intelligent Transportation Systems, Vol.1, No. 4, pg. 179-189, 2000.

[3] Federal Aviation Administration Task Order white Paper, “Literature Review of Conflict Resolution Research” 2010.

[4] Bowe, A., Lauderdale, T., "Selecting conflict resolution maneuvers based on minimum fuel burn," Digital Avionics Systems Conference (DASC), 2010 IEEE/AIAA 29th , vol., no., pp.1.A.4-1-1.A.4-9, 3-7 Oct. 2010.

[5] Erzberger, H., McNally, B. D., Foster, M., Chiu, D., and Stassart, P., "Direct-To Tool for En Route Controllers," ATM '99: IEEE Workshop on Advanced Technologies and their Impact on Air Traffic Management in the 21st Century, Capri, Italy, 26-30 Sep. 1999.

[6] Erzberger, H., "Automated Conflict Resolution for Air Traffic Control", 25th International Congress of the Aeronautical Sciences (ICAS), Hamburg, Germany, 2006.

[7] Erzberger, H., Lauderdale, T., Chu, Y.C., "Automated Conflict Resolution, Arrival Management and Weather Avoidance For ATM", 27th International Congress of the Aeronautical Sciences (ICAS), Nice, France, 2010.

[8] Meyn, L., Windhorst, R., Roth, K., Drei D.V., Kubat, G., Manikonda, V., Roney, S., Hunter, G., and Couluris, G., Build 4 of the airspace concepts evaluation system. Proc AIAA Modeling and Simulation Technologies Conference and Exhibit, 2006.

[9] Paglione, M. M., Santiago, C., Crowell, A., Oaks, R.D., “Analysis of the Aircraft to Aircraft Conflict Properties in the National Airspace System”, American Institute of Aeronautics and Astronautics Guidance, Navigation, and Control Conference, AIAA 2008-7143, Honolulu, Hawaii, August 18-21, 2008.

[10] European Organisation For the Safety of Air Navigation, 2004, "User Manual For The Base of Aircraft Data (BADA)", Revision 3.6.

[11] Federal Aviation Administration, Operational Data Reporting Requirements (OPSNET) url: https://aspm.faa.gov/opsnet/sys/Default.asp , November 4, 2011.