SELECTING CONFLICT RESOLUTION MANEUVERS BASED ON MINIMUM FUEL BURN

Aisha Bowe, NASA Ames Research Center, Moffett Field, CA
Todd Lauderdale, NASA Ames Research Center, Moffett Field, CA

Abstract

The effects of selecting conflict resolution maneuvers based on minimum delay are compared to resolution selection based on minimum fuel burn. The algorithm used in this study is designed to support an automated separation assurance capability for next generation air traffic management systems. The algorithm resolves detected conflicts that are projected to be between three and twenty minutes prior to loss of separation. A total of nine fast-time simulations were conducted, each representing thirty six hours of traffic on a "low weather," high volume day with mixed aircraft types, flight phases and conflict geometries. The test matrix varied airspace region and resolution selection criteria. System-wide effects such as the number of conflicts, fuel burn, delay, and maneuver type are analyzed and compared to the same metrics when maneuvers are selected based on delay. When selecting resolutions based on fuel burn, the cumulative fuel burn of the system decreases by 27% and the delay increases by 25% when compared to resolutions selected based on minimum delay. Results indicate that speed maneuvers are the most efficient when selecting resolutions based on minimum fuel burn. Horizontal and vertical maneuvers were executed with similar frequency when comparing delay and fuel burn.

Introduction

Air traffic demand is projected to increase significantly in the upcoming years [1]. In order to meet the forecasted levels, the human workload associated with conflict detection and resolution must be reduced to assure system safety and performance. Automated separation assurance systems are proposed as a way to efficiently separate aircraft in highly dense traffic situations up to two to three times current levels.

There are numerous algorithms proposed to provide separation assurance in the future air traffic system [2]. With any automated resolution tool, the type of resolution selected is based on some cost function. Two costs associated with conflict resolution maneuvers are delay and fuel burn. These two costs are closely correlated, but not necessarily the same. There have been several previous studies of conflict resolution algorithms in which the preferred resolution is selected based on delay [3, 4]. These studies demonstrate that the algorithms are robust to high traffic demand and can find resolutions that have low average delay, but they have not been examined for fuel efficiency.

The purpose of the current study is to compare the system performance of a conflict resolution algorithm in realistic traffic scenarios when selecting resolutions based on minimum delay to system performance when selecting resolutions based on minimum fuel burn. The total costs in terms of fuel burn and delay are compared between the two resolution selection criteria. Also, the total number of conflicts is compared to determine if there is any adverse impact on safety. Finally, an examination of the different types of resolutions selected in the two cases is performed to understand how the selection criteria may affect specific resolution scenarios.

The paper is organized as follows: a brief overview of the simulation setup is provided in the next section and is followed by the equations that govern fuel burn. The results are then presented along with a discussion of their implications, concluding with a summary of the findings and a recommendation for future work.

Simulation Setup

In this study the Airspace Concept Evaluation System (ACES) is used to simulate the National Airspace System (NAS) in a fast-time simulation. The conflict resolution algorithm evaluated is the Advanced Airspace Concept (AAC) Autoresolver [4, 5]. For this simulation ACES computes the delays and the fuel burn values used by the Autoresolver to select preferred resolutions.

Test Bed

ACES is a fast-time, agent-based simulation of the NAS that uses four-degree-of-freedom equations based on the Base of Aircraft Data (BADA) to generate aircraft trajectories [4]. 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 4D 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. Negotiation of resolution trajectories between aircraft operators and/or the air navigation service provider were not modeled. Neither 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].

Test Article: AAC Autoresolver

The AAC Autoresolver is a strategic conflict resolution algorithm designed to deconflict aircraft that are predicted to lose separation more than two minutes in the future. For this study, every minute of simulation time the future trajectories of all the 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. Taking into account characteristics such as aircraft type, speed and airspace boundaries, the resolver calculates a future route composed of waypoints, speeds and altitudes which 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 trial resolution trajectory based on this route.

In order for the resolution to be viable, it must resolve the primary conflict, be free of predicted losses of separation with the primary aircraft in the conflict, as

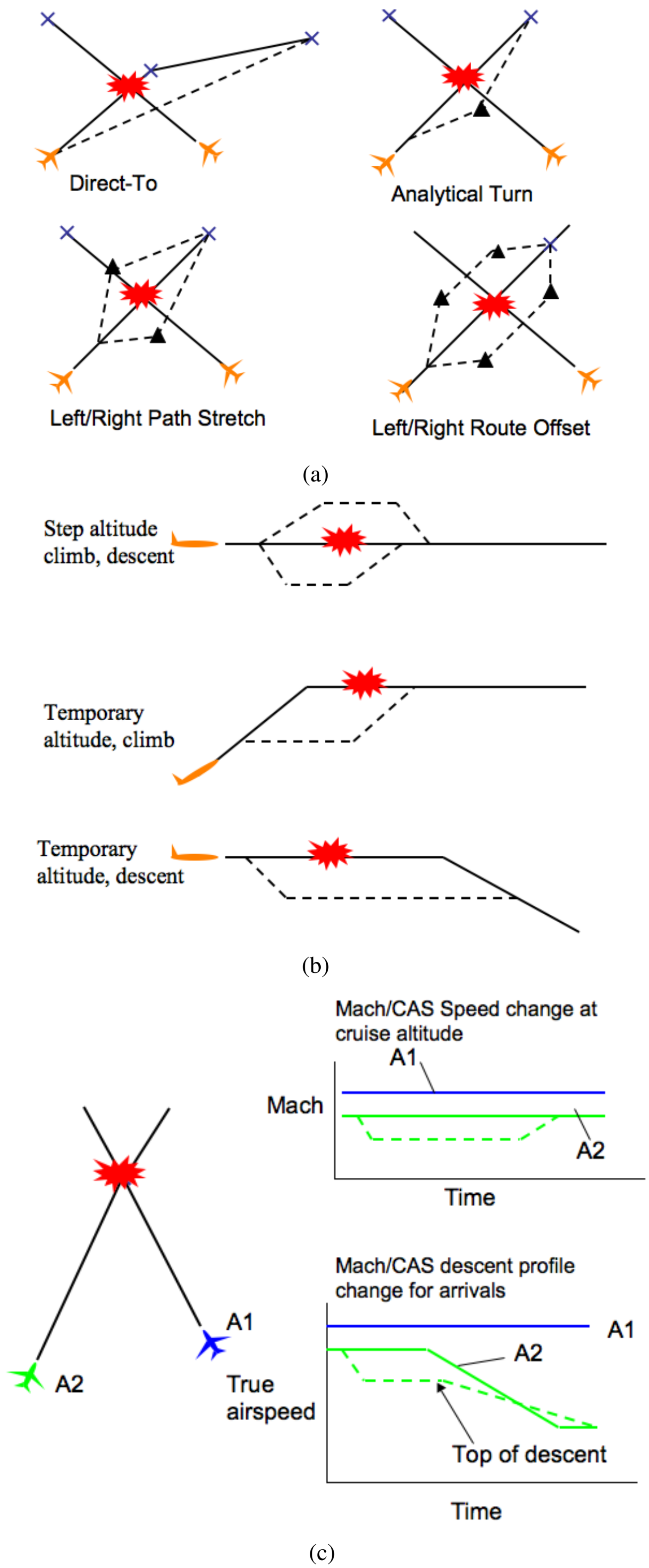


Figure 1. Resolution trajectories of type (a) horizontal, (b) vertical, and (c) speed [5].

well as any other aircraft in the simulation for 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 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 tried.

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 for the resolution trajectory is subtracted from the aircraft weight for the original trajectory. 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 seven successful resolutions per aircraft in conflict for a total of fourteen available 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 sent to ACES for implementation. Further discussion regarding the design of the algorithm and the types of resolutions that are generated is presented in [4,5].

Procedure

To illustrate the differences between selecting conflict-resolution maneuvers based on delay and selecting resolution maneuvers based on fuel burn, a test plan was developed to isolate this variable. Two cases were simulated for each specific scenario: one with resolution selection based on minimum delay and one with resolution selection based on minimum fuel burn.

Demand Set

Flight operations over a 36-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 specific day was selected because it represented a "low weather," high volume day in the NAS.

Simulated Airspace

For this study, the Autoresolver provided conflict resolution services for a single Air Route Traffic Control Center at a time. Three centers were used to analyze the algorithmic performance with different types of air traffic flows. These centers were Indianapolis (ZID), Minneapolis (ZMP) and Atlanta (ZTL). The simulation included all types of air traffic for each center: departures, overflights and arrivals for air carrier, business and general aviation. Each of the demand sets provided thirty six hours of simulated air traffic transitioning through the selected airspace.

Two simulations were run per center, one for fuel burn and one for delay for a total of six simulations. Although the data set used in the simulations consisted of 62,970 flights, the number of flights that passed through each center differed because of differences in the size and layout of the airspace along with the traffic volume and composition. Table 1 shows the experiment test matrix and number of flights that passed through each center.

Center	Case	Flights Simulated
ZID	Delay	5413
ZID	Fuel Burn	5413
ZMP	Delay	8577
ZMP	Fuel Burn	8577
ZTL	Delay	10049
ZTL	Fuel Burn	10049

Table 1. Experiment test matrix and simulated flights.

Fuel Burn Equations

By default, the AAC Autoresolver selects the preferred conflict resolution based on minimum delay. For this study, the algorithm was modified to allow for selection of the preferred resolution based on minimum fuel burn. Since the computation of fuel burn is critical to the results presented here, the equations used to calculate this fuel burn will now be discussed.

The fuel burn required for a resolution for this simulation is computed by ACES using aircraft-specific coefficients selected from the Base of Aircraft Data [7]. 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.

The BADA fuel model uses the thrust-specific fuel consumption, η, measured in kilogram/minute/kilonewton and the thrust, T, to determine the nominal fuel flow, f_{nom}. This is given by:

$$f_{nom} = \eta T, \tag{1}$$

where η, for jet aircraft, is:

$$\eta = C_{fl}\left(1 + \frac{V_{TAS}}{C_{f2}}\right). \tag{2}$$

In this equation, C_{f1} and C_{f2} are two thrust-specific fuel consumption coefficients reported in the BADA dataset and V_{TAS} is the true airspeed.

The thrust depends on the aircrafts phase of flight. For the majority of the resolutions discussed in this study, the aircraft is in the level cruise portion of flight. In this phase, the thrust is equal to the drag and can be represented by the following:

$$T = \frac{\rho C_D S (V_{TAS})^2}{2}, \tag{3}$$

where ρ is the air density, C_D is the drag coefficient reported by BADA, and S is the wing reference area.

For idle thrust descent conditions the fuel flow, f_{min}, is measured in kilogram/minute as:

$$f_{min} = C_{f3}\left(1 - \frac{h}{C_{f4}}\right), \tag{4}$$

where h is the altitude above sea level in feet, C_{f3} is the first descent fuel flow coefficient and C_{f4} is the second descent fuel flow coefficient. For climb portions of flight, the fuel flow is still given by equation 1, but the thrust is computed based on the type of climb performed by the aircraft.

These equations show that, among other things, the fuel burn is a function of thrust, airspeed, and altitude. Even though these equations are only an approximation of the actual fuel burn of an aircraft, they will be used as the true fuel burn for the results which follow.

Results

The six simulation runs presented in Table 1 were performed, and the results were analyzed. Three aspects of the performance of the conflict resolution algorithm were compared between the delay cases and the fuel burn cases: system safety, system efficiency, and resolution selection.

Although results were compiled and analyzed on an individual Center basis, no significant differences were observed between Centers. Accordingly, the results are presented in the aggregate.

Safety

The main focus of this study is on how the resolution selection criterion affects system efficiency and resolution selection. However, it is also important to determine whether this selection criterion impacts safety. As a first-order look at safety, two metrics were analyzed: the total number of conflicts and the percentage of conflicts successfully resolved. A significant increase in the number of conflicts as a result of selecting resolutions based on fuel burn might suggest increased risk.

The total number of conflicts for the delay cases and the fuel burn cases is presented in Table 2. Selection based on fuel burn leads to approximately 5% more conflicts than selection based on delay. This increase may be a by-product of the resolution selection process, but it is not considered large enough to have an impact on system safety. To illustrate this point, only one conflict remained unresolved in all of the delay cases, and only one conflict remained unresolved in all of the fuel burn cases. So, over 99.98% of all conflicts were resolved when either selection criterion was used.

	Delay	Fuel Burn
Total Conflicts	4984	5234
Resolved Conflicts	4983	5233
Percent Resolved	99.98%	99.98%

Table 2. Conflict resolution results.

Efficiency

The operational efficiency of the resolution trajectories produced by the algorithm is important in understanding the advantages and disadvantages of resolution selection based on fuel burn or delay. Successful resolution trajectories that require less fuel or reduce delay are preferable to those that cause an increase in either quantity.

Cumulative Delay

Delay is the time associated with executing resolution maneuvers. Figure 2 shows the cumulative delay for the system when selecting resolution trajectories based on delay or fuel burn. As expected, the results show that the cumulative delay when selecting resolutions based on delay is 25% less than the cumulative delay when selecting resolutions based on fuel burn. This reduced delay can result in economic and system efficiency advantages to selecting resolutions based on minimum delay.

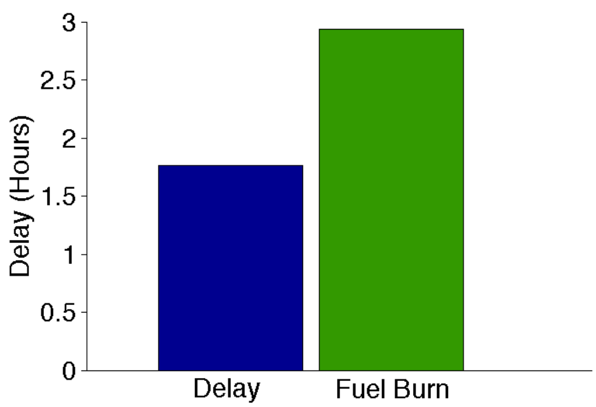
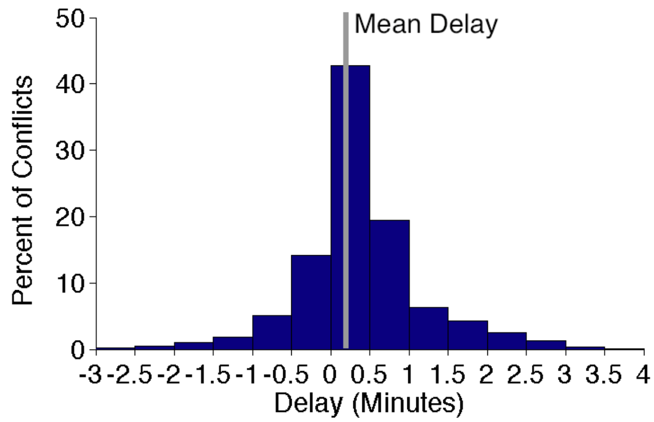


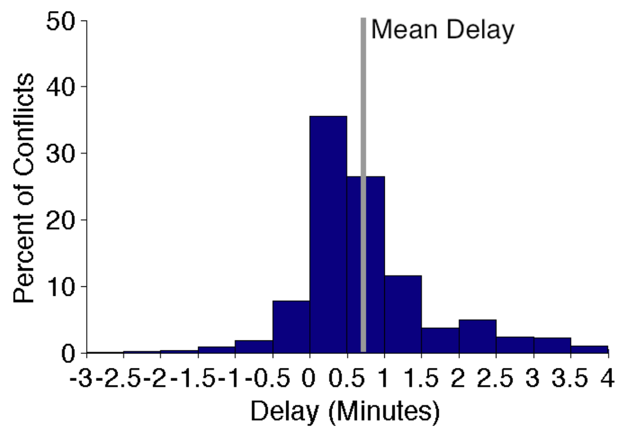
Figure 2. Cumulative delay.

The histograms in Figure 3 provide insight into how the delay imposed by the algorithm is distributed for the two resolution selection criteria. These histograms are divided into 30-second time bins with negative times corresponding to resolutions which generate time savings relative to the selected original trajectory. Negative delay results when Direct-To resolutions (Figure 1(a)) are included within the successful resolutions. Direct-To resolutions resolve conflicts by redirecting the aircraft to a downstream waypoint. This directly bypasses a dog-leg in the flight plan. Figure 3(a) shows the delay for the cases where resolutions are selected based on minimum delay, and Figure 3(b) shows the delay for the cases where resolutions are selected based on minimum fuel burn.

The mean delay for resolutions in Figure 3(a) is 18 seconds. Over 22% of the resolutions in these cases result in a time savings. These values can be contrasted with the results for fuel-burn selection cases shown in Figure 3(b). The mean delay for these resolutions is 40 seconds, and only 11% of the resolutions result in a time savings. It can be seen that for the fuel-burn cases the histogram is more heavily weighted to the right.



(a)



(b)

Figure 3. Delay histograms for (a) minimum delay and (b) minimum fuel burn.

Cumulative Fuel Burn

Figure 4 shows the cumulative fuel burn required for conflict resolution for the system when selecting resolutions based on delay or fuel burn. As expected, when the algorithm is selecting based on fuel burn the cumulative fuel burn of the system is 27% less than the fuel burn for delay selection. This fuel-burn reduction could lead to environmental and economic reasons for selecting resolutions maneuvers based on minimum fuel burn. There are tradeoffs evident when comparing Figure 2 for delay selection and Figure 4 for fuel burn selection, and these tradeoffs will be discussed further in the Environmental and Economic Impact Section.

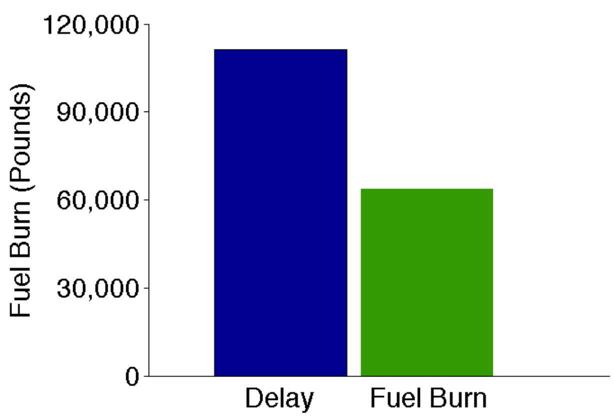


Figure 4. Cumulative fuel burn.

The histograms in Figure 5 show how the fuel burn is distributed when selecting resolutions based on delay, Figure 5(a), or fuel burn, Figure 5(b). The figures are divided into 50-pound bins, with negative fuel amounts indicating a fuel savings for the trial plan with respect to the original trajectory. Such fuel savings are the result of Direct-To resolutions.

The mean fuel burn for the delay selection case is 22 pounds. It can be seen from Figure 5(a) that, for the delay case, the fuel burn distribution is more heavily weighted to the right side of zero, with only a small percentage of resolutions resulting in a fuel savings. In contrast, when selecting resolutions based on fuel burn (Figure 5(b)), the distribution is more evenly weighted with nearly half of the resolutions producing a fuel savings. For this case the mean fuel burn is 12 pounds.

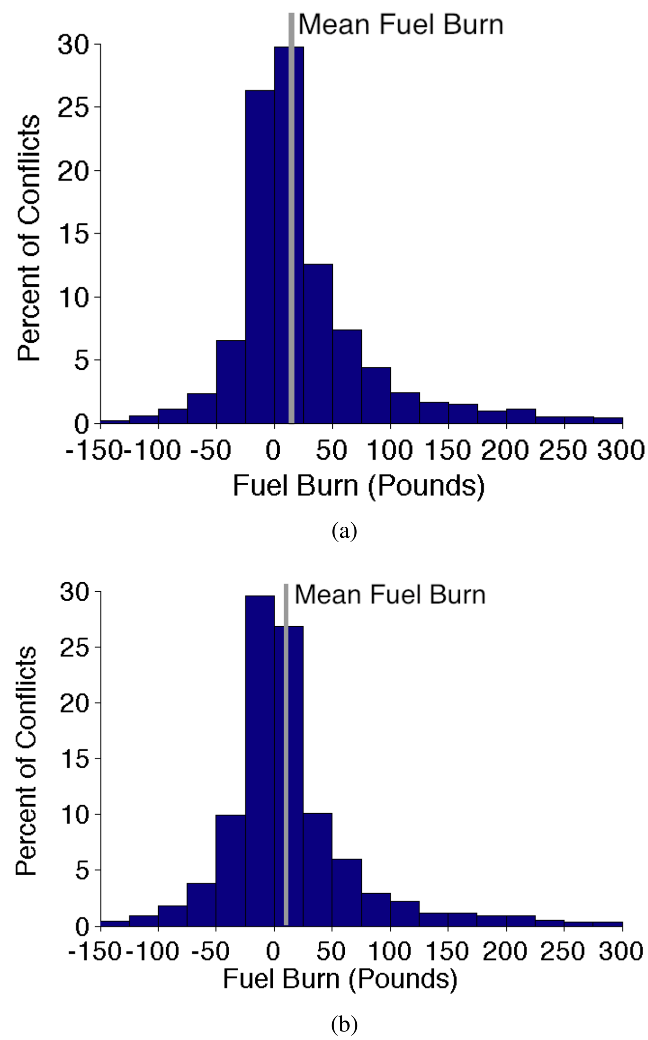


Figure 5. Fuel burn histograms for (a) minimum delay and (b) minimum fuel burn.

Resolution Selection

In the previous sections, the system-wide trade-offs of selecting conflict resolutions based on minimum fuel burn or minimum delay were presented. Since these two different cases produce different results for total delay and total fuel burn, it is interesting to try to comprehend the mechanism for this difference. As a first attempt to understand the underlying differences, the impact of this selection criterion on the types of resolutions that are likely to be selected will now be analyzed. For this analysis, the many different types of resolutions attempted by the Autoresolver will be categorized in three groups according to the dominant method of conflict resolution: horizontal maneuvers, vertical maneuvers, and speed maneuvers.

Figure 6 shows the percentage of each type of maneuver selected for the two cases. When selecting based on fuel burn, the percentage of vertical maneuvers is about equal to the percentage when selecting based on delay. The percentage of speed maneuvers based on fuel burn is higher by 3.5% and the percentage of horizontal maneuvers is lower by 3%.

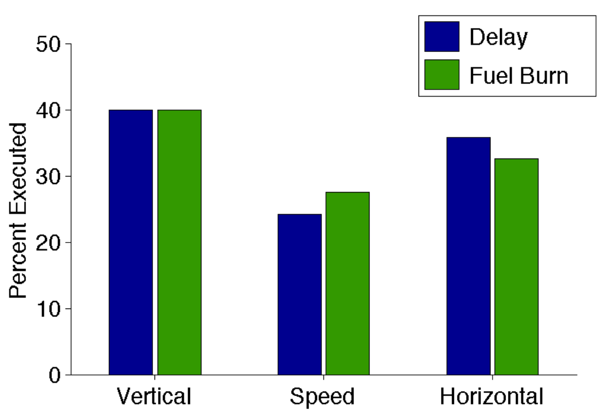
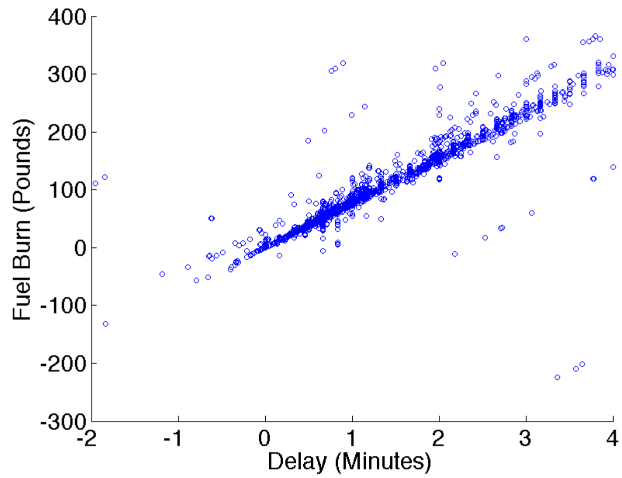


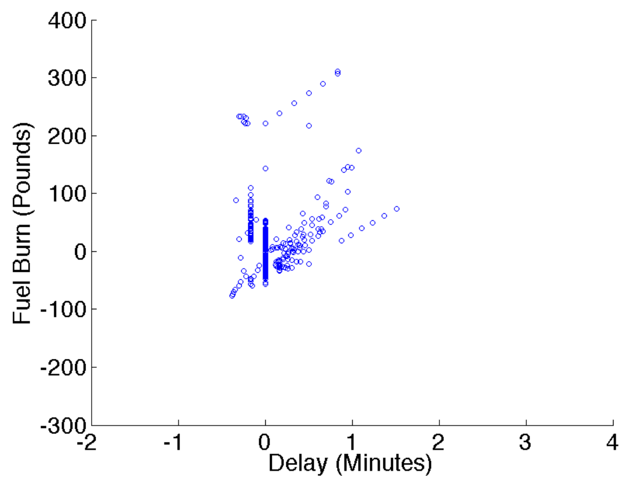
Figure 6. Selected maneuver types

To understand the causes of this difference in maneuver selection, the relationship between delay and fuel burn are plotted for a single aircraft type for the Atlanta Center case. Figure 7 shows this relationship for all resolutions (not just selected ones) for Airbus 319 aircraft in the simulation. A single aircraft type was selected to reduce the fuel flow variance.

Generally, it might be thought that reducing the delay will reduce fuel burn. Figure 7(a) shows that this is



(a)



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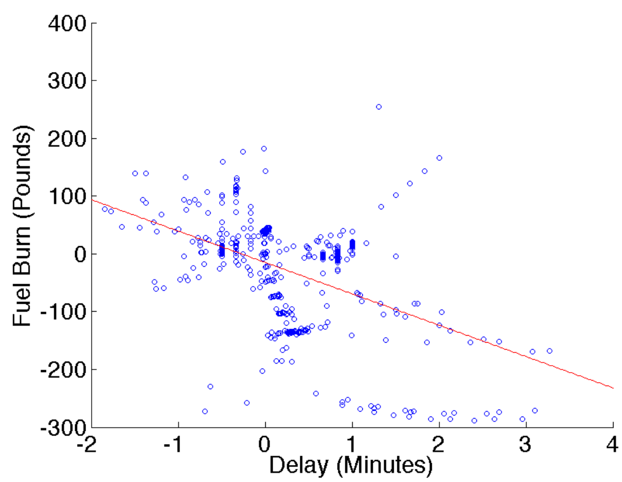

(c)

Figure 7. Fuel burn versus delay for Airbus 319 aircraft for (a) horizontal maneuvers, (b) vertical maneuvers, and (c) speed maneuvers.

indeed the relationship for horizontal maneuvers. There is a linear variation where increasing delay leads to increasing fuel burn. The multiple trend lines evident in the figure are from resolutions at different altitudes and at different cruise speeds.

The relationship is a bit more complex for vertical resolutions (Figure 7(b)). Many of the resolutions plotted in this figure show a linear positive correlation, but there are some cases where resolutions with negative delay led to positive fuel burn. These are probably from altitude-hold resolutions where the aircraft maintains a lower altitude than the cruise altitude for a certain amount of time to avoid a conflict.

For speed resolutions (Figure 7(c)) the relationship between delay and fuel burn does not show clearly identifiable trends therefore a linear regression was included to aid in identification. There are many resolutions where increases in delay lead to decreases in fuel burn. These are speed resolutions that command a reduction of cruise speed to avoid the conflict. This speed reduction results in less fuel burn, but greater delay. The relationships between delay and fuel burn for speed resolutions illustrate the differences between the resolution selections shown in Figure 6 as well as the differences in cumulative delay and fuel burn shown in Figures 2 and 4.

Environmental and Economic Impact

The development of algorithms in support of automated separation assurance should not only be concerned with safe and efficient operations but also be environmentally and economically responsible. In recent years public concern has grown regarding the potential impact of the byproducts of aviation, particularly noise and emissions. It is estimated that aircraft world-wide contribute about 3.5% of the total radiative forcing (a measure of change in climate) off all human activities, and this percentage is projected to grow [8]. A contributor to this projected growth is the impending expansion in the level of air traffic demand in the NAS. Ensuring safe and environmentally responsible systems is of utmost importance if the aviation industry is to meet projected levels of growth and demand.

Fuel Burn

The potential reduction in fuel burn presented in the results section amounted to 10 pounds per resolution when selecting resolutions based on fuel burn. Expanding on this result using a jet fuel (Jet A) price of 220.1 cts/gal and 5,233 the number of resolved conflicts in the three centers from Table 2, the total savings in US dollars over the course of the 36-hour period is $16,963 which would amount to approximately $4 million per year [9].

This fuel cost translates to a savings in carbon dioxide emissions. From the above it can be seen that the selection based on minimum fuel consumption would save approximately 52,330 pounds of fuel. Using the weight of the jet fuel, the amount of carbon dioxide released can be determined. The Energy Information Administration estimates that burning a gallon of jet fuel emits 21 pounds of carbon dioxide [10]. One gallon of jet fuel weighs on the order of 6.79 pounds per gallon, which would bring the amount of carbon dioxide saved to 161,845 pounds. The projected savings would come at no cost to airlines, as they do not require any modification of existing aircraft or controller practices. The reduction in emissions and cost stems from a change in the way resolutions are selected within the automated conflict resolver.

Delay

The effects of delay play an important role in airspace management and decision making. For shorter delays the system-wide impact can be relatively small and result in longer flight times that influence the direct operating cost of the airline. However, longer delays can propagate through the system as the day progresses. These delays can prove to be disruptive to activities such as crew scheduling, gate scheduling and even delay later flights.

Although selecting resolutions based on minimum fuel burn results in fuel savings, delay is increased. The mean delay of resolutions when selecting based on fuel burn is 40 seconds. Using a delay cost of $20 per minute for the number of resolved conflicts in the three centers from Table 2, and assuming the number of seats in the aircraft is between 65-150, the cost of the delay is $69,773 [11]. This is significantly more than the cost of the fuel savings associated with the same number of resolved conflicts when selecting conflict resolutions based on minimum fuel burn. However, cost is only one of several factors that must be taken in to account when evaluating resolution selection criterion.

Conclusion

The AAC algorithm was modified to select the preferred resolution based on minimum fuel burn by comparing the aircraft weight at a point along the original trajectory with a common point downstream.

In fast-time simulation of three airspace regions, the resolution trajectories were found to incur an average of 40 seconds more delay when selecting conflict resolutions based on minimum fuel burn. This represents a 25% increase over resolutions selected based on minimum delay. Similarly, the trajectories required an average of 10 pounds more fuel when selecting based on delay when compared to selection based on fuel burn.

A preference for speed maneuvers was established when selecting resolutions based on minimum fuel burn. Horizontal and vertical maneuvers were found to be less fuel efficient than speed maneuvers when selecting based on fuel burn. When executing horizontal and altitude maneuvers, optimization based on delay was found to be more efficient.

Changing the selection criteria from delay to fuel burn was found to have no impact on the ability of the algorithm to successfully detect and resolve conflicts. Despite the modifications, the algorithm was able to successfully detect and resolve 99.98% of all conflicts regardless of the resolution selection criterion.

Future Work

In this study, speed maneuvers were found to be the most fuel efficient when selecting resolutions based on minimum fuel burn. However, the number of speed resolutions executed in comparison to horizontal and vertical resolutions is significantly less. Further modification of the algorithm to generate a greater number of speed resolutions would yield higher fuel savings. Similarly, an additional reduction in fuel consumption can be achieved by combining Direct-To resolutions with speed changes. This would serve to reduce the speed by an amount that would cancel the negative delay of the resulting Direct-To resolution.

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