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A Study of Conflict Resolution Timeliness and Impact of Horizontal Maneuver Parametric Settings

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The tradeoff between efficiency and trajectory uncertainty is considered when evaluating how early to initiate a conflict resolution maneuver. Four fast-time simulations are conducted employing a well-established prototype conflict detection and resolution algorithm to quantify the fuel and delay penalties associated with deferring resolution maneuvers in order to increase confidence in the conflict prediction. Additionally, the effects of using finer resolution when selecting conflict-resolution heading maneuvers are evaluated. Results indicate that early initiation of resolution maneuvers reduces airborne delay and fuel consumption, but only slightly. This finding suggests that it may be operationally desirable to forgo the modest delay and fuel benefits associated with earlier maneuvers in order to buy down the uncertainty that is inherent in trajectory predictions with longer time horizons.

I. Introduction

Air traffic demand is predicted to increase significantly over the next decade[1]. The increased traffic will lead to increased workload for human air traffic controllers, which is a limiting factor on the amount of traffic that can be safely routed through the National Airspace System (NAS). One way to address the associated human workload impact is the development of conflict detection and resolution algorithms. The primary purpose of conflict detection and resolution algorithms is to aid in the prediction of potential losses of separation (LOS) and determine how to resolve them. A LOS is defined as an event in which the distance between the two aircraft becomes less than 5 nautical miles laterally and 1,000 feet vertically. Many conflict detection and resolution algorithms have been developed with approaches that range from genetic algorithms[2,3] to programming models[4,5] to force fields[6,7] and air traffic control heuristics[7]. One automated capability that is currently being tested and used for large-scale simulations is the Autoresolver, developed by the National Aeronautics and Space Administration (NASA)[9,10].

Despite the exhaustive nature of the Autoresolver, it currently chooses a resolution that is as far in advance of the LOS as possible, without regard for the possibility that a more efficient maneuver is available closer to the conflict. The time in advance of the predicted LOS at which a resolution maneuver is initiated is referred to as the Resolution Initiation Time (RIT). In previous work, time horizons (i.e., tactical and strategic) in the realm of conflict detection and resolution have been examined by Chaloulos, et al.[11] and Paielli[12]. The present study serves as an extension to previous research which concluded that there is a benefit to utilizing more strategic maneuvers in terms of decreasing both delay and fuel consumption[13]. However, the experiment's design facilitated the testing of only four RITs. Also, maneuvers were executed when the conflict was detected, preventing examination of how the most efficient maneuver evolved as the two aircraft approached LOS. As an extension to this previous research, the present study examines a continuous range of RITs and configures the Autoresolver so that maneuvers are not executed when a conflict is detected, permitting examination of evolution of the conflict resolution maneuvers as the two aircraft approach LOS. The present research examines the effect that RIT has on the delay and fuel consumption as well as the effect of a finer resolution of path-stretch parametric settings on system-wide delay and fuel consumption.

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It was expected that increasingly strategic maneuvers would result in more efficient resolution maneuvers in terms of delay and fuel consumption due to the fact that maneuvers that are started farther in advance of a conflict require less extreme deviations from the aircraft's current path. This is depicted in Fig. 1. Further, it was expected that the addition of more types of path stretch maneuvers would magnify the effect of the RIT on the delay and fuel consumption. Understanding the role the RIT plays in maneuver efficiency has the potential to be very beneficial to the development of efficient conflict detection and resolution algorithms.

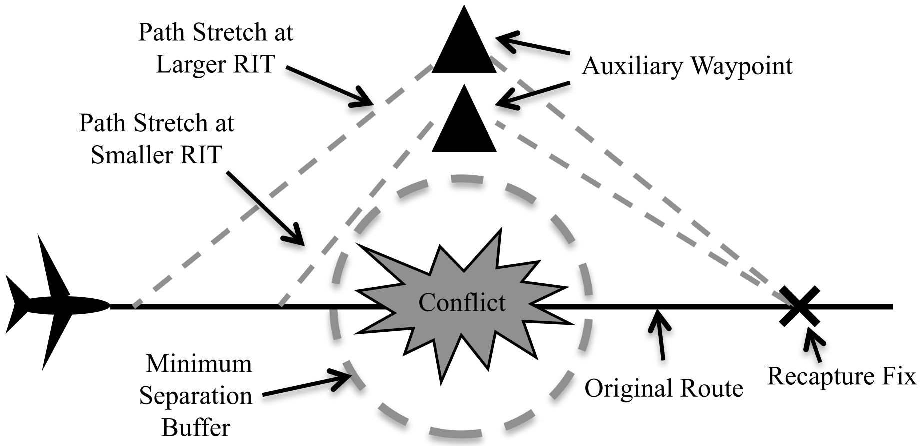

Figure 1: Difference Between Maneuvers at Larger and Smaller RITs

II. Background

The Autoresolver is a conflict resolution algorithm that resolves predicted LOS and uses an exhaustive process in which it iteratively constructs and evaluates a multitude of different horizontal, vertical, and speed maneuvers for both aircraft projected to be involved in the conflict. Throughout this process, the utility develops a list of maneuvers that it deems "successful"; that is, maneuvers that successfully alter the flight path for one of the two aircraft such that the primary conflict is resolved and where the maneuvered aircraft remains conflict-free for a specified period of time after the maneuver is initiated. From this list of successful maneuvers, the Autoresolver selects the most efficient maneuver to resolve the conflict. The Autoresolver can be configured to select this maneuver based on delay efficiency, fuel efficiency, or a combination of the two. Further, the Autoresolver can be configured to "execute" the maneuver, in which case it re-routes one of the aircraft, or it can be configured to select the most efficient maneuver without executing the maneuver. In the latter configuration, the Autoresolver will perform all of the same steps as described, but will not maneuver either of the aircraft. This process of constructing and evaluating maneuvers is repeated at one-minute intervals until both aircraft reach LOS.

Path stretch maneuvers are commonly-used horizontal maneuvers defined by adding an auxiliary waypoint to the flight's path to avoid a potential conflict, shown in Fig. 2. In conflicts that utilized a path stretch maneuver, only one aircraft was maneuvered while the other aircraft remained on its nominal flight path.

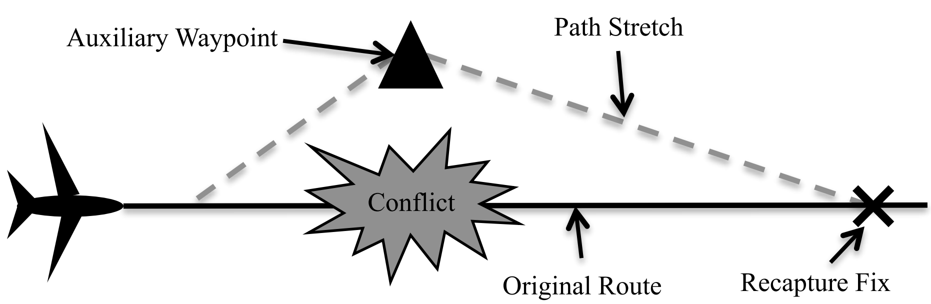

Figure 2: Path Stretch Resolution

III. Method

A. Autoresolver Configuration

The Autoresolver was configured to choose resolution maneuvers based on the minimum delay without regard to the fuel consumed by the aircraft during the maneuver. The Autoresolver was configured to choose the most efficient maneuver, but not execute the maneuver (i.e., the flight path for both aircraft remained unaltered). The maximum RIT at which maneuvers could be generated for a conflict was 12 minutes and the minimum RIT was 5 minutes, yielding a 7-minute maximum window in which maneuvers could be analyzed. These maneuvers were generated at one-minute intervals following the detection of the conflict.

B. Experiment Procedure

A 3-hour, NAS-wide air traffic scenario simulating 4,800 flights was used in NASA's Airspace Concept Evaluation System (ACES) fast-time simulation software[14]. No weather or flight path uncertainty was simulated, and analyses included only conflicts in which both aircraft were enroute; that is, both aircraft were greater than 20 minutes from their respective arrival fixes. By not altering the flight paths of aircraft projected to lose separation, the experiment facilitated an investigation of how the most efficient resolution maneuver evolved as the two aircraft approached LOS, which can change depending on various factors, including the conflict geometry (i.e., conflict angle, speeds or aircraft, etc.) or proximate traffic.

The experiment investigated the effect of added path stretch parametric settings. The two settings changed were the number of available turn-out angles and the number of available delay ellipses, depicted in Fig. 3. The turn-out angle is the angle used by the maneuvering aircraft to turn away from its original route toward the added auxiliary waypoint, while the delay ellipse is used by the Autoresolver algorithm to determine how much delay will result from a path-stretch maneuver that places the auxiliary waypoint somewhere on the ellipse. Path stretch maneuvers with auxiliary waypoints on the same delay ellipse will have approximately the same delay. Four simulations were conducted in which these two variables were altered (see Table 1). Aircraft turn dynamics were modeled when calculating trajectories from path-stretch maneuvers. The set of values used in the baseline simulation represent the values that have historically been used by the Autoresolver (i.e., the default values), while those used in the angle, ellipse, and combination simulations represent a finer resolution of values. Performing simulations with the new values and comparing the results to the baseline simulation were expected to give insight into whether or not enhancements should be made to the Autoresolver algorithm that account for these settings.

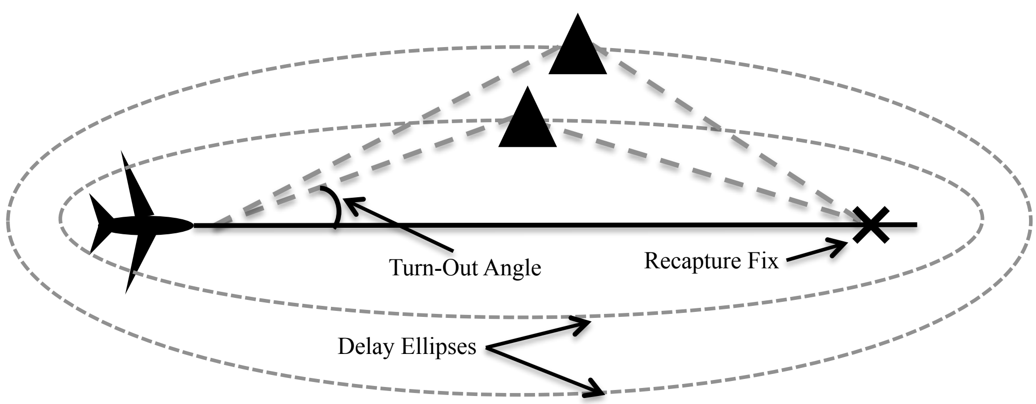

Figure 3: Path Stretch Geometry Variables

The research focused on the system-wide effect on two measures of a maneuver's efficiency: delay and fuel consumption. Delay is defined as the additional flight time incurred compared to the original, unaltered flight path. The fuel consumption refers to the amount of fuel consumed during the maneuver. Both measures are widely used to assess the system-wide effect of conceptual changes to air traffic control procedures and in the development of concepts for conflict detection and resolution algorithms. The analysis is separated by the effect of the independent variables on the delay and on the fuel consumption.

Table 1: Changes Made to the Path Stretch Geometry Variables

	Delay Ellipse Values (seconds)	Turn-Out Angle Values (degrees)
Baseline Scenario	5, 10, 15, 22.5, 30, 37.5, 45, 52.5, 60, 75, 90, 105, 120	40, 60, 120, 180, 300
Angle Scenario	5, 10, 15, 22.5, 30, 37.5, 45, 52.5, 60, 75, 90, 105, 120	5, 10, 20, 30, 40, 50, 60, 90, 120, 180, 300
Ellipse Scenario	2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, 25, 27.5, 30, 32.5, 35, 37.5, 40, 42.5, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90	40, 60, 120, 180, 300
Combination Scenario	2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, 25, 27.5, 30, 32.5, 35, 37.5, 40, 42.5, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90	5, 10, 20, 30, 40, 50, 60, 90, 120, 180, 300

Analyses performed to assess the effect of the independent variables included various summary statistics as well as inferential statistics on regression slopes and differences among means in an analysis of variance (ANOVA). For the regression and ANOVA models, all normality and homoscedasticity assumptions were met. The regression model included a term for the RIT as well as three indicator terms to represent the four levels of the simulation. The ANOVA model included the simulation as well as an effect of the maneuver type (e.g., path stretch, vertical, speed, etc.) as a blocking variable to account for some of the error in the model. All determinations of significance were based on an $\alpha=0.05$ level, meaning a p-value less than 0.05 indicated a significant effect or relationship.

IV. Results and Discussion

A. Delay

Table 2 reports the percentage of conflicts, resolved by all maneuver types, in which a more delay-efficient maneuver is available in the future for each RIT. For example, at 11 min before LOS in the baseline simulation, 66.67% of conflicts have at least one maneuver that is more delay efficient in the future (i.e., at 10 min before LOS or at 9 min before LOS, etc.). In all four simulations, there is a more delay-efficient maneuver in greater than 50% of conflicts when the RIT is nine minutes or greater. This percentage, however, falls below 50% when the RIT becomes less than nine minutes in all configurations. When comparing the four simulation types for a given RIT, the difference in percentages is fairly small, suggesting that the increased number of available path stretch maneuvers has little effect on the resolution maneuvers in terms of RIT.

Table 2: Percentage of Conflicts where a Better Maneuver is Available Closer to LOS

Time in Advance of Conflict	Baseline	Angle	Ellipse	Combination
11-minutes	66.67%	66.67%	55.55%	58.33%
10-minutes	66.67%	64.10%	61.54%	60.87%
9-minutes	62.50%	58.90%	55.56%	53.49%
8-minutes	29.86%	30.04%	26.12%	26.18%
7-minutes	37.27%	36.51%	34.44%	35.38%
6-minutes	18.16%	17.78%	15.02%	16.23%

Figure 4 depicts the mean delay as a function of the RIT for all maneuver types (e.g., path stretch, speed, vertical, etc.) Negative delay values result from cases when maneuvers save time when compared to the original, unaltered trajectory. The regression analyses show that there are statistically significant negative slopes, indicating that delay decreases as the RIT increases. In this case, the slope is interpreted as the increase in seconds of delay for every minute that the maneuver is initiated earlier; therefore, the analysis indicates for every minute the RIT decreases (i.e., every minute the two aircraft get closer to the LOS), the delay that results from the maneuver decreases by approximately one to two seconds, depending on the simulation type. Furthermore, this finding supports the data reported in Table 2: there is a more efficient maneuver available closer to the conflict. The analysis revealed there are no combinations of RIT and simulation that produce a nonzero slope when all other terms are held constant (p=0.42-0.69), indicating that the four slopes are not statistically different from each other. This, like the data reported in Table 2, suggest that finer resolution of path stretch parametric values have no relationship with the RIT in terms of the delay that results from a maneuver. Further, despite the statistical significance of the slopes, the operational significance is marginal. For example, if an average of two seconds is saved for every minute the two aircraft get closer to LOS, a maneuver can save approximately 14 seconds if it delays the start of a maneuver 7 minutes. While statistically significant, it is highly unlikely that 14 seconds is a noticeable difference for pilots, air traffic controllers, or commercial aircraft passengers. Meanwhile, the probability of finding a successful maneuver, regardless of efficiency, is somewhat reduced as the aircraft approach LOS.

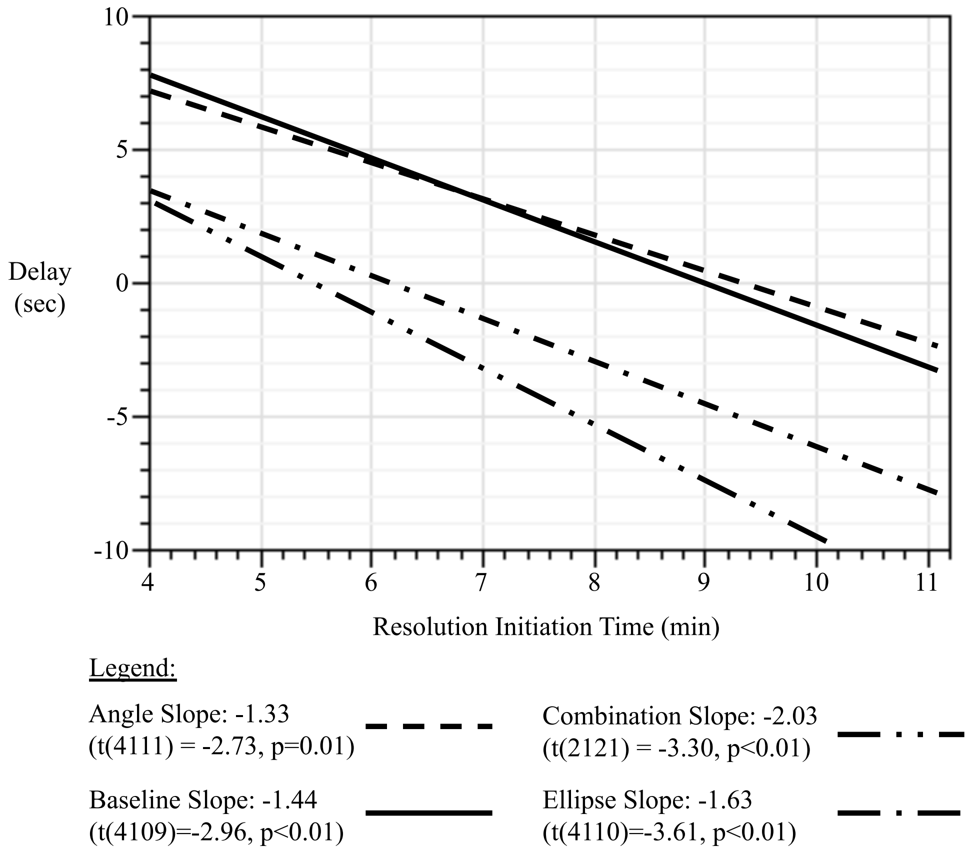

Figure 4: Delay as a Function of RIT for all Maneuver Types

Figure 5, which reports the results from solely conflicts that utilize a path stretch maneuver, reveals trends similar to those examined in Fig. 4. However, none of the four slopes is statistically significant, indicating there is no relationship between the RIT and the delay (i.e., the slope is zero), regardless of the scenario type. Furthermore, since there is no evidence that any of the four slopes is nonzero, there is no combination of scenario type and RIT that yields a nonzero slope (p=0.64-0.89), further indicating a lack of relationship between the simulation type and the RIT in terms of delay. One explanation is that the exhaustive nature of the Autoresolver algorithm formulates and constructs so many maneuvers that it is finding the most efficient maneuver possible, regardless of how far the aircraft are from LOS. The addition of more potential path stretch maneuvers (due to the introduction of a finer resolution of path-stretch parametric values) allowed the algorithm to be even more exhaustive, possibly causing the lack of a significant relationship between the RIT and the simulation type. Testing a finer resolution of parametric values for other maneuver types, such as vertical maneuvers or speed maneuvers, could potentially reveal a significant relationship between the RIT and simulation type in terms of the delay incurred by the maneuver.

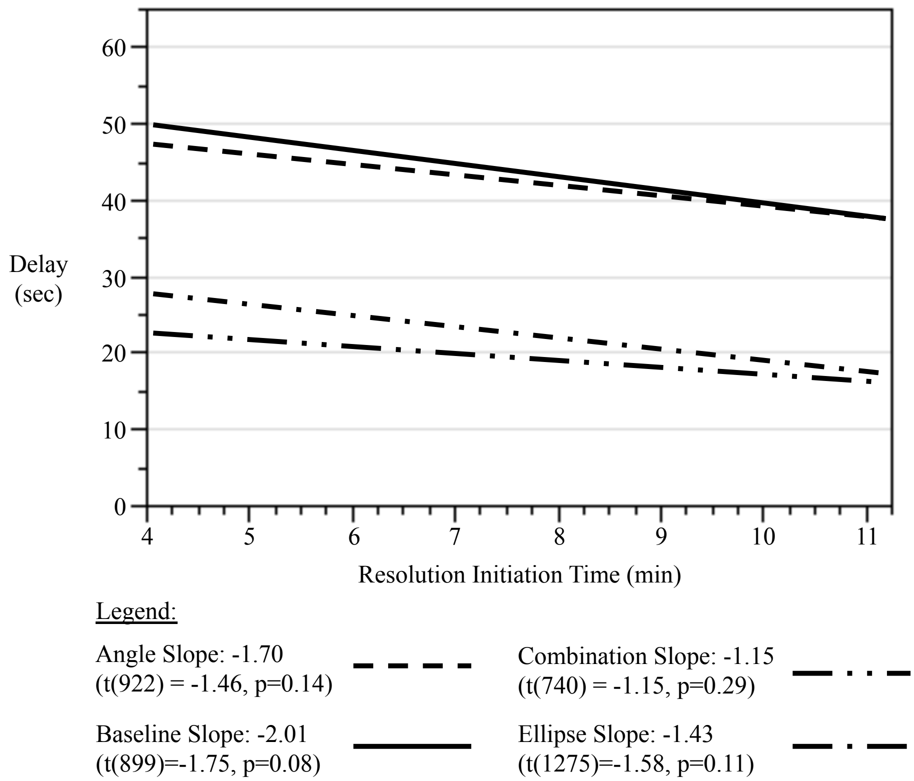

Figure 5: Delay as a Function of RIT for Path Stretches

Since there seems to be a system-wide delay benefit to the different simulation types despite the lack of a significant relationship between the delay and the RIT, an ANOVA was performed to assess any significant differences among the mean delay (across all RIT values) of the four simulations and included conflicts that were resolved with all maneuver types. Rather than assess the relationship between the RIT and the delay, as was done in the previous regression analyses, the ANOVA compared the mean delay, aggregated across all maneuver types, for each simulation type. The ANOVA revealed a significant main effect of the simulation type ($F(3,14446)=83.32$, $p<0.01$), indicating a significant difference between the four simulations in terms of mean delay. A Tukey's Honest Significant Difference (HSD) post-hoc analysis, which calculates the significance of the differences among the levels of the simulation type, is shown in Table 3. The "Least Square Mean" in the table represents the mean delay incurred per conflict as a result of the maneuver chosen. The test revealed the combination simulation yielded the lowest amount of delay, followed by the ellipse simulation then the angle and baseline simulations. There was no significant difference in delay between the angle and baseline simulations, indicating that solely adding more path stretch angles does not provide a delay benefit compared to the baseline settings. Further, the lack of difference between the baseline and delay simulations suggests that the delay benefit of the combination simulation is driven mostly by the added ellipse values.

Table 3: Tukey's HSD Groupings for the Effect of Simulation on Delay

Simulation	Least Square Mean	Tukey Grouping*
Baseline	24.03 sec	A
Angle	23.69 sec	A
Ellipse	16.70 sec	B
Combination	14.49 sec	C

*Levels not connected by the same letter are significantly different

B. Fuel Consumption

Table 4, which shows the percentage of conflicts in which a more fuel-efficient maneuver is available in the future, suggests it is almost always better to delay the start of a resolution. Also, the data shows there is a less than 50% probability that a better maneuver is available after a RIT of 6 minutes, indicating 6 minutes may be the ideal RIT in terms of fuel consumption. The percentage of more fuel-efficient future maneuvers is generally higher for all levels than the corresponding values for delay. Furthermore, the percentages are generally smaller for the combination scenario than for any of the other three scenarios. This suggests that the Autoresolver is finding the most fuel-efficient maneuver earlier due to the additional path stretch maneuvers being considered.

Table 4: Percentage of Conflicts Where a Better Maneuver is Available Closer to LOS

Time in Advance of Conflict	Baseline	Angle	Ellipse	Combination
11-minutes	72.22%	72.22%	66.67%	58.33%
10-minutes	76.92%	79.49%	74.36%	69.57%
9-minutes	72.22%	71.23%	70.83%	62.79%
8-minutes	63.84%	63.77%	63.11%	57.94%
7-minutes	58.82%	58.78%	57.53%	53.16%
6-minutes	44.55%	44.65%	43.73%	46.08%

In the graphs presented in this section, the slopes represent the regression coefficient for the independent variable, RIT, as it affects the dependent variable, fuel consumption. Figure 6, specifically, presents the relationship between fuel consumption and RIT for each of the four simulation types. The slopes were formulated using all maneuver types. None of the slopes displayed in Fig. 6 is statistically significant, indicating there is no relationship between the RIT and fuel consumption for any of the simulations (i.e., the slopes are zero). As expected (since there are no nonzero slopes), no combination of RIT and simulation type produces a statistically significant relationship (p=0.66-0.98). The fact that these results are different from the delay results may be attributable to the fact that maneuvers are chosen by the Autoresolver based on which provides the least delay without regard to the maneuver's fuel consumption. Therefore, the Autoresolver may be executing maneuvers with low delay and high fuel consumption (e.g., a speed-increase maneuver), effectively minimizing the effect of the RIT on the maneuver's fuel consumption.

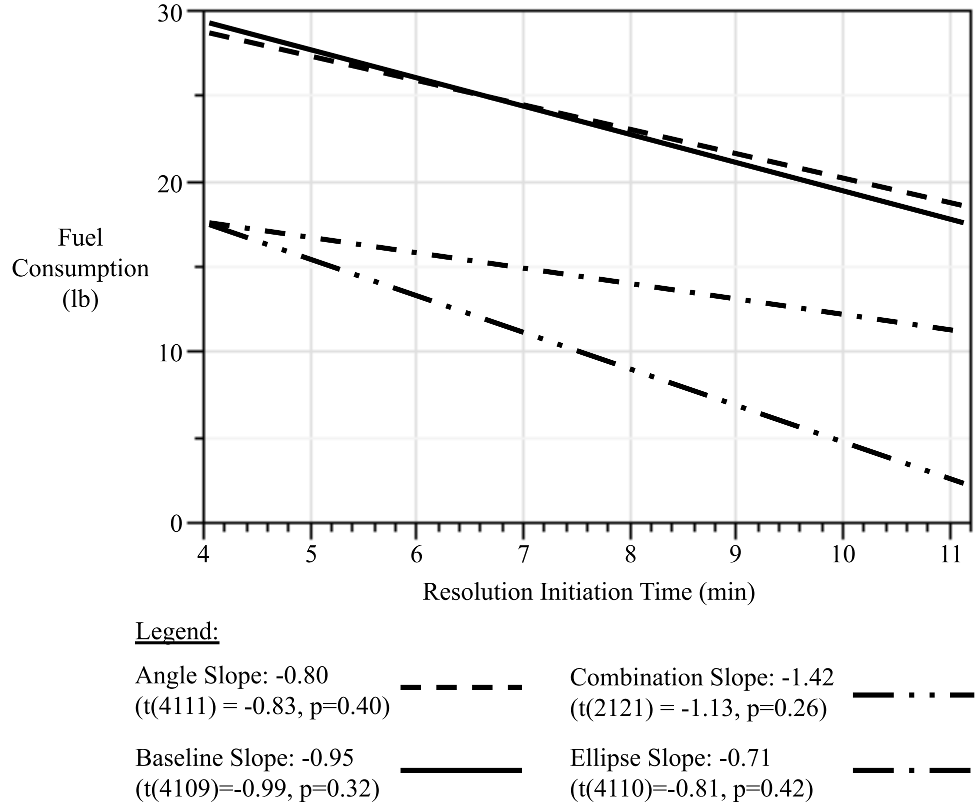

Figure 6: Fuel Consumption as a Function of RIT for All Maneuver Types

Finally, the trends shown in Fig. 7, which reports the relationships between the RIT and fuel consumption for only path stretch maneuvers, are very similar to those reported for all maneuvers. Again, none of the slopes is significantly different from zero, and no nonzero slopes exist for any combination of simulation and RIT (p=0.68-0.89), again indicating there is no difference in slope among the four simulation types. Furthermore, despite the lack of a significant relationship between the two independent variables, the overall fuel consumption seems to be lower for the combination and ellipse scenarios compared to the baseline and angle scenarios. As with the data presented in Fig. 6, the lack of a relationship between the RIT and fuel consumption may be attributable to the fact that the Autoresolver chooses maneuvers based on delay without regard to the associated fuel consumption.

To examine whether there is a significant difference in the mean fuel consumption per conflict between the four simulations, an ANOVA was performed. As with the delay, there was a significant effect of the simulation for the fuel consumption response ($F(3,14446)=29.43$, $p<0.01$). The Tukey's HSD post-hoc analysis, shown in Table 5, reports there is no significant difference between the combination and ellipse scenarios, nor between the angle and baseline scenarios (the "Least Square Mean" in the table represents the mean fuel consumed per conflict as a result of the maneuver chosen). However, the mean fuel consumption per conflict for the ellipse and combination scenarios is significantly smaller than those for the baseline and angle scenarios. These results suggest that much of the benefit comes from the added ellipse values as opposed to the added angle values, and the benefit of the combination scenario is likely driven by the added delay ellipse settings rather than the added turn-out angles.

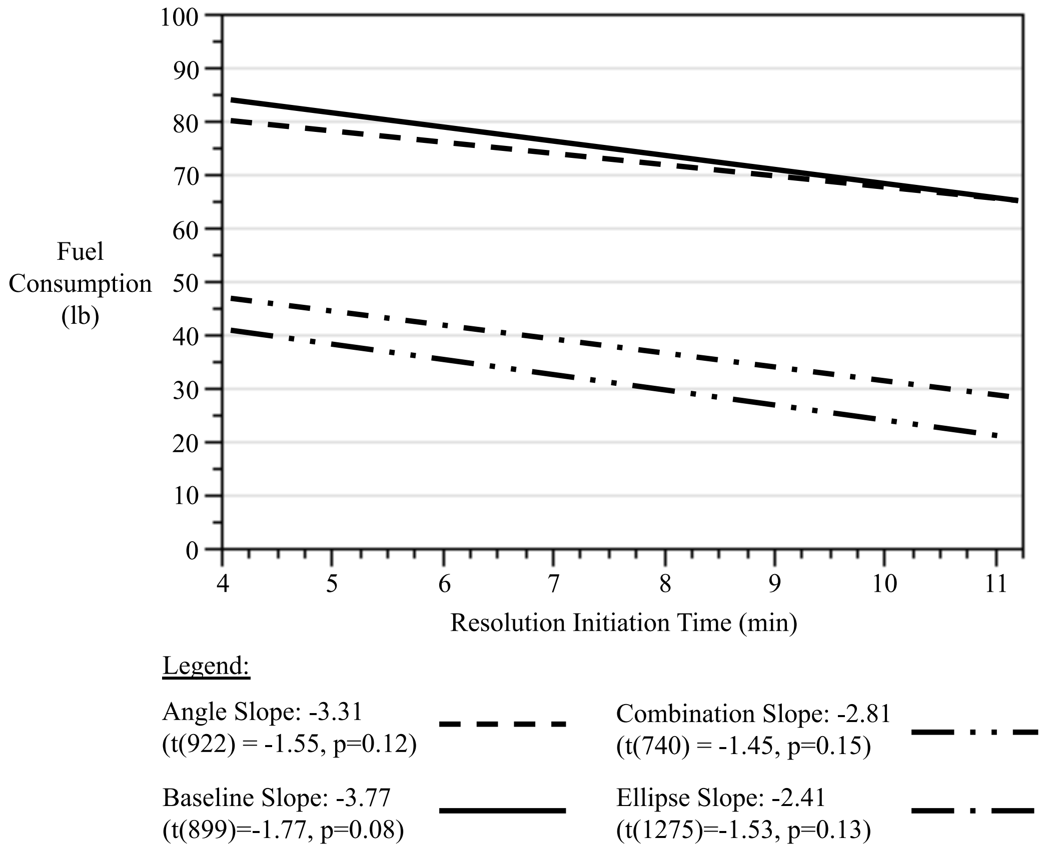

Figure 7: Fuel Consumption as a Function of RIT for Path Stretches

While these findings suggest delaying the start of a maneuver is associated with no added delay or fuel consumption penalty, it is worth considering the risk associated with the delay of a maneuver. Intuitively, as the two aircraft approach LOS, it should be expected that the probability of formulating a conflict-free maneuver would decrease. While this may be true in the current, human-controlled airspace system, the data set used for this research suggests this is not the case. The Autoresolver reliably formulates a successful resolution with RITs of four minutes and greater. This provides further evidence that the Autoresolver's exhaustive nature is finding the most efficient maneuver possible.

Table 5: Tukey's HSD Groupings for the Effect of Simulation on Fuel Consumption

Simulation	Least Square Mean	Tukey Grouping*
Baseline	28.53 lb	A
Angle	28.16 lb	A
Ellipse	18.60 lb	B
Combination	16.75 lb	B

*Levels not connected by the same letter are significantly different

V. Conclusions

It was expected that more strategic maneuvers would be more efficient, but the lack of significant regression slopes for the fuel consumption provide evidence against this expectation. The regression coefficients for delay, although statistically significant, are very small, indicating that any benefit in delay of more strategic maneuvers is marginal (i.e., not operationally significant). It was also expected that the effect of the RIT would be magnified with the addition of more available path stretch maneuvers (i.e., more turn-out angles and delay ellipses), as indicated by regression slopes with larger magnitudes. This was not supported for either the delay or the fuel consumption. Furthermore, the ANOVAs performed on the delay and fuel consumption indicate that, while RIT has little influence, the addition of a finer resolution of path stretch parametric values provide a significant benefit for the mean delay and fuel consumption incurred per conflict. This benefit seems to be mainly driven by the added delay ellipse values; the contribution by the added turn-out angles was marginal.

Since RIT has a marginal effect, there is little penalty to delaying the start of a maneuver, especially if it is likely that a more efficient maneuver will present itself. The exhaustive nature of the Autoresolver also seems to decrease any risk inherent to delaying the start of a maneuver. However, future research should consider the change in safety and reliability as a function of the RIT to ensure delayed maneuvers do not create unresolvable conflict states. The marginal effect of the RIT is an advantageous quality of the algorithm, because it indicates that, even if the algorithm is not resolving a conflict as soon as possible, a resolution with similar or better performance attributes is still likely to be available in the future. This can be especially beneficial in analysis on the uncertainty of flight paths, since flight path uncertainty decreases as the time window decreases. Enhancements to the algorithm should focus on the addition of delay ellipse values (as opposed to the addition of turn-out angles) since they seemed to drive the system-wide delay and performance benefits.

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