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# Exploratory Study of Interoperability Between Tactical and Strategic Separation Assurance Functions

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**This paper evaluates the interoperability of two elements of the ground-based Advanced Airspace Concept (AAC) separation assurance system: Tactical Separation-Assured Flight Environment (TSAFE) and Autoresolver. Even though they are intended to be independent safety layers of AAC, they still need to work well together to keep aircraft safely separated. However, their interoperability has not been investigated thoroughly. Among other desired behavior, it would be ideal if no maneuver by either system were followed up by a conflict prediction and resolution by the other. Unfortunately, this is not the case because each uses its own distinct trajectory predictor and conflict detection algorithm with time frames that overlap. In fast-time simulations, TSAFE made a conflict prediction after an Autoresolver resolution for the same flight pair about 1 percent of the time and for the maneuvered flight about 2 percent of the time. Extending the threshold for predicted time to loss of separation at which Autoresolver could issue maneuvers from the baseline of 8 minutes to 12 minutes reduced the frequency of these cases by at least half with fewer resolutions and less delay and fuel burn while maintaining zero losses of separation. By comparison, increasing the horizontal separation standard for Autoresolver maneuvers from 7 nautical miles to 10 and 12 nautical miles had little to no effect.**

## I. Introduction

AIR traffic demand is expected to more than double over the next 20 years,[1] but air traffic controller workload limits airspace capacity. As such, it is expected that higher levels of automation for separation assurance (SA) are needed in the Next Generation Air Transportation System (NextGen) to maintain airspace safety and efficiency. The Advanced Airspace Concept (AAC) is a ground-based separation assurance system that is comprised of four independent layers of conflict detection and resolution (CD&R) for different time horizons.[2-3] Its strategic, longer-range CD&R function, the Autoresolver (AR), finds solutions for conflicts (i.e., predicted losses of separation based on the standard horizontal and vertical criteria of 5 nmi and 1000 ft, respectively) that are projected to occur at least 2 minutes in the future. Its shorter-range counterpart, the Tactical Separation-Assured Flight Environment (TSAFE), operates on a time frame of 0 to 3 minutes. Human-in-the-loop simulations demonstrated that Autoresolver could be used simultaneously with TSAFE conflict detection[4] and/or TSAFE conflict resolution[5] as decision support tools for air traffic controllers in near-term operations. However, the interactions between these systems were not analyzed. The interoperability of Autoresolver and TSAFE will be evaluated in-depth for the first time in this paper. The other two AAC safety layers, collision avoidance (Traffic Collision Avoidance System, or TCAS) and pilot see-and-avoid, are already present in current operations and are beyond the scope of this study.

The Autoresolver finds comprehensive solutions for three types of separation assurance problems that comprise a significant portion of en route air traffic controller workload: aircraft-to-aircraft separation, arrival sequencing, and weather avoidance.[6] Evaluation of the aircraft separation component in fast-time simulations with traffic levels up to three times current operations and no trajectory prediction uncertainty found that it successfully resolved 99.5% of conflicts.[7] A parametric study on the relative significance of six sources of trajectory prediction uncertainty (weight, wind, cruise speed, descent speed, top of descent (TOD), and maneuver initiation time) found that it resolved at least 90% of conflicts.[8] Several methods have been effective at preventing unresolved conflicts by reducing missed and false alerts, such as adjusting trajectory predictions for climbing flights in real-time using only currently available track and atmospheric forecast data,[9] using a characterization of trajectory prediction errors for probabilistic conflict prediction,[10] and applying safety buffers during climb[11] and around TOD.[12] However, there will always be conflict situations that cannot be detected and resolved by Autoresolver due to trajectory prediction uncertainty.

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TSAFE is designed to independently identify all conflicts that Autoresolver does not resolve and find heading and/or altitude maneuvers to keep flights safely separated for at least 3 minutes. TSAFE was evaluated using about 100 actual operational error cases that resulted in loss of separation (LOS). Compared to the Conflict Alert system that is currently used in the National Airspace System (NAS), TSAFE had about half as many missed alerts and false alerts.[13] In fact, after adding altitude amendments to correct for controller input errors and omissions, TSAFE detected and resolved all operational error cases in replay simulations.[14] However, it is not clear that TSAFE and Autoresolver will work well together for the full breadth and variety of conflict situations that come up in actual operations because few studies have run both systems concurrently. In the post-simulation analysis of one study, TSAFE was applied to about two dozen LOS cases that were not resolved by Autoresolver; it generated an alert for each conflict at least 1 minute before loss of separation.[15] In addition to this, a recent human-in the-loop simulation tested Autoresolver conflict detection and resolution and TSAFE conflict detection using three scenarios of 30-45 minutes each in 3 sectors of Fort Worth Center.[4] Post-simulation analysis of the 124 TSAFE alerts found that 14 were false alerts, with all but one involving at least one climbing flight. By comparison, this paper evaluates both systems in multi-Center (fast-time) simulations using 3 hours of aircraft takeoff data (about 4800 flights total).

The remainder of this paper is organized as follows. The next section provides background information on key differences between Autoresolver and TSAFE that lead to interoperability issues. Following that is a description of the fast-time simulations that were run to evaluate interoperability. The section after that contains an analysis of the differences in TSAFE and Autoresolver conflict predictions generated in fast-time simulations without resolutions that foreshadowed some of the results when Autoresolver issued resolution maneuvers. After that is an analysis of the interoperability of TSAFE conflict detection and Autoresolver conflict resolution in terms of the percentage of Autoresolver maneuvers that were followed up by a TSAFE alert. Several possible means of reducing the frequency of this undesirable event are discussed afterwards. Lastly, the findings of this research are summarized.

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## II. Background

AAC is a multi-layer, ground-based separation assurance system that has been adapted in previous work for both near-term operations as a controller decision support tool[4-5] as well as further-term operations as a highly automated system.[2-3] Autoresolver and TSAFE independently generate trajectory predictions, perform conflict detection, and issue conflict resolution maneuvers on time frames that overlap. This can lead to interoperability issues that affect controllers and/or pilots to different degrees depending on the concept of operations. One particularly undesirable situation that is the focus of this paper is when a resolution maneuver issued by one algorithm is followed up by a conflict prediction and resolution by the other because this can disrupt the implementation of the initial maneuver.

### A. Trajectory Prediction

Trajectory prediction is the foundation of every separation assurance system. While TSAFE has its own internal trajectory predictor, Autoresolver requires an external algorithm to generate trajectories for conflict detection and resolution. In this paper, Autoresolver uses the Multi-Purpose Aircraft Simulation (MPAS) trajectory predictor of the Airspace Concept Evaluation System (ACES) simulation platform.[16] Autoresolver and TSAFE intentionally use different trajectory predictors since any inherent weaknesses of a common trajectory predictor will negatively affect the performance of both systems. However, the conflict predictions and resolutions generated by these algorithms will differ due to fundamental differences in the trajectory predictors used. For instance, MPAS and TSAFE model vertical profiles for climbing flights in two distinct ways. At a high level, MPAS generates four-degree-of-freedom trajectories using the aircraft equations of motion and aircraft performance models that were derived from the Base of Aircraft Data (BADA).[17] It models a maximum-thrust climb at a constant Calibrated Airspeed until the aircraft achieves a target Mach value, which is then maintained until the flight reaches its cruise altitude (controlling the lift coefficient within the BADA range). By comparison, TSAFE uses BADA as a lookup table for vertical rates when generating altitude profiles for climb trajectory predictions.

### B. Conflict Prediction

Autoresolver and TSAFE also use different numbers and types of trajectory predictions and conflict prediction criteria. This can lead them to make different conflict predictions both in terms of the flight pairs that are identified as well as the predicted horizontal and/or vertical separation. In addition, since the conflict prediction algorithm is also used to check resolution maneuvers for conflicts before being issued to aircraft, these differences may lead one algorithm to issue a maneuver that is not deemed conflict-free by the other algorithm. The latter might then issue its own resolution maneuver, which is undesirable because it would disrupt the implementation of the initial maneuver by pilots and/or controllers.

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One of the primary differences between Autoresolver and TSAFE conflict detection is that the former utilizes a single 4-D trajectory prediction for each flight while the latter computes two trajectory predictions per flight: a dead-reckoning (DR) projection of current velocity and one based on flight plan (FP) cruise altitude and route waypoints (if provided). This is because the shorter-range TSAFE is designed to be more conservative and have fewer missed alerts[13] since it is the safety net for conflicts that are not resolved by Autoresolver. In the vertical dimension, both TSAFE trajectory predictions use the altitude envelope defined by the DR projection and the aircraft type-specific BADA vertical rates.[17] If the flight is in transition (i.e., climbing or descending), then this envelope is defined by the fast and slow vertical rates; otherwise, TSAFE uses the standard BADA vertical rate.

TSAFE compares all four combinations of DR and FP trajectory predictions for a flight pair and issues an alert if the predicted separation for any of them is less than its conflict alerting criteria.[13] If two or more comparisons lead to a conflict prediction, then the shortest time to initial LOS and the smallest predicted separation are reported even if they are from different comparisons. Combined with the fact the Autoresolver and TSAFE time frames overlap and other reasons (see Table 1), TSAFE and Autoresolver conflict predictions that are made at the same time and for the same flight pair can have substantially different predicted times to LOS and horizontal and/or vertical separation.

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**Table 1 Comparison of Key Features of Autoresolver and TSAFE**

| Feature | Autoresolver | TSAFE |
|---|---|---|
| Time Frame | Strategic (2 to about 20 minutes prior to LOS) | Tactical (0 to 3 minutes prior to LOS) |
| Horizontal Trajectory Prediction Types | FP-based | FP-based and DR |
| Vertical Trajectory Prediction | Baseline | Altitude envelope defined by DR projection and BADA vertical rates |
| Number of Trajectory Prediction Comparisons (per conflict pair) | One | Four (FP-based and DR trajectories for both flights) |
| Trajectory Prediction Range | Fixed | Variable (depends on trajectory type, phase of flight, and conformance to flight plan route) |
| Conflict Prediction Frequency | Fixed cycle (e.g., once every 12 seconds) | Variable (whenever a new track update or flight plan amendment is received) |
| Conflict Prediction Criteria | Fixed (e.g., 5 nmi horizontally and 1000 ft vertically) | Variable (depends on flight phase, conflict geometry, and predicted time to loss of separation) |
| Conflict Resolution Separation Criteria | Fixed (7 nmi horizontally or 1000 ft vertically) | Fixed (5 nmi horizontally and 1000 ft vertically (level), or 7 nmi horizontally and 1400 ft vertically (in transition)) |
| Arrival Management Capability | Yes | No |
| Weather Avoidance Capability | Yes | No |

### C. Conflict Resolution

The Autoresolver and TSAFE conflict resolution algorithms are also very different. For instance, TSAFE only sends out altitude or heading maneuvers and never both at the same time. On the other hand, Autoresolver can also issue both altitude and heading resolutions as well as speed, path stretch, and parallel offset maneuvers and various combinations of these different types. In addition, while Autoresolver specifies how to return a maneuvered flight back to its original route, heading, and/or altitude, TSAFE does not and instead relies upon an external algorithm such as Autoresolver for this function. Thus, it is especially undesirable for a resolution issued by one algorithm to be followed up by a conflict prediction and resolution by the other.

## III. Experiment Setup

TSAFE was integrated into ACES,[16] which was already capable of running simulations with Autoresolver. This allowed both Autoresolver and TSAFE to be run simultaneously using a common simulation platform for the first time. ACES itself is a fast-time, gate-to-gate simulation and modeling tool of the NAS that uses aircraft performance models derived from BADA to generate flight trajectories.[17] Since the main purpose of this paper was to investigate

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the fundamental interoperability issues between Autoresolver and TSAFE, no uncertainties were incorporated into any of the simulation runs.

### A. Baseline Autoresolver Parameters

Table 2 lists the Autoresolver parameters that are most relevant to this paper and their baseline values. First, the maximum conflict detection look-ahead time was 59 minutes to accommodate holding patterns. Next, Autoresolver used the standard horizontal and vertical separation criteria of 5 nmi and 1000 ft, respectively, for conflict detection. The baseline conflict resolution start time was 8 minutes, which prevented Autoresolver from issuing maneuvers to conflict pairs with predicted time to LOS greater than 8 minutes. These maneuvers were also required to maintain at least 7 nmi of horizontal separation or 1000 ft of vertical separation for a minimum of 12 minutes.

**Table 2  Baseline Autoresolver Parameters**

| Parameter | Baseline Value |
|---|---|
| Conflict Detection Maximum Look-Ahead Time | 59 min |
| Conflict Detection Horizontal Separation Criterion | 5 nmi |
| Conflict Detection Vertical Separation Criterion | 1000 ft |
| Conflict Resolution Start Time | 8 min |
| Conflict Resolution Conflict-Free Time | 12 min |
| Conflict Resolution Horizontal Separation Criterion | 7 nmi |
| Conflict Resolution Vertical Separation Criterion | 1000 ft |

### B. Baseline TSAFE Parameters

Table 3 is a similar list of important TSAFE CD&R parameters and their baseline values. First, as mentioned before, TSAFE's maximum look-ahead time is 3 minutes. However, the actual time frame depends on the conflict situation (e.g., two level flights), conformance to flight plan routes, and predicted time to LOS as well as the types of trajectory predictions (flight plan-based or dead-reckoning) being compared. TSAFE performs CD&R based on a separation ratio metric. In general, it is the maximum of the ratio of the horizontal and vertical separation of the two flights relative to the separation standards of 5 nmi and 1000 ft, respectively:

$$S = \max\left(\frac{h_{sep}}{5}, \frac{v_{sep}}{1000}\right) \tag{1}$$

TSAFE uses a separation ratio of 1.1 for conflict detection and a separation ratio of 1.4 for conflict resolution. However, there are some subtleties to the separation ratio metric based on the phases of flight.[13] It is straightforward in the horizontal dimension where the separation ratios translate to 5.5 nmi for detection and 7.0 nmi for resolution. By comparison, in the vertical dimension, the criterion is 1100 ft for detection and 1400 ft for resolution only when flights are in transition; otherwise, it is 1000 ft.

**Table 3  Baseline TSAFE Parameters**

| Parameter | Baseline Value |
|---|---|
| Maximum Prediction Time Horizon (all trajectories) | 3 min |
| Conflict Detection Horizontal Separation Criterion | 5.5 nmi |
| Conflict Detection Vertical Separation Criterion (in transition) | 1100 ft |
| Conflict Detection Vertical Separation Criterion (not in transition) | 1000 ft |
| Conflict Resolution Horizontal Separation Criterion | 7.0 nmi |
| Conflict Resolution Vertical Separation Criterion (in transition) | 1400 ft |
| Conflict Resolution Vertical Separation Criterion (not in transition) | 1000 ft |

### C. Experiments with Autoresolver Resolution

A parametric study of the Autoresolver conflict resolution start time and required horizontal separation criterion was performed to determine if interoperability with TSAFE could be improved using different values. A flight data

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set with three hours of air traffic data from the peak traffic time of May 17, 2002 was simulated for the entire NAS. It contained roughly 4800 flights, with 1835 flights in the air at the peak.

First, two baseline simulations were run: one with Autoresolver resolutions enabled, and the other one without. Then, simulations were run for two Autoresolver conflict resolution parameters using the bolded values in Table 4. As mentioned earlier, the main interoperability metric for these simulations was the frequency of a TSAFE conflict alert after an Autoresolver resolution.

**Table 4 Experiments to Evaluate TSAFE Interoperability with Autoresolver Conflict Resolution**

| Experiment Variable | Number of Conditions | Values |
|---|---|---|
| Autoresolver Conflict Resolution Start Time | 3 | **5**, 8, **12** min |
| Autoresolver Conflict Resolution Horizontal Separation Criterion | 3 | 7, **10**, **12** nmi |

For the Autoresolver conflict resolution start time, both shorter (5 minutes) and longer (12 minutes) values were evaluated due to the potential tradeoffs of each. On the one hand, a longer Autoresolver conflict resolution start time could reduce the likelihood of subsequent TSAFE alerts because there will generally be more maneuver options and greater initial separation between flights. However, if more Autoresolver maneuvers are issued, this could increase the overall number of Autoresolver resolutions that are followed up by a TSAFE alert and/or system delay. On the other hand, a shorter Autoresolver conflict resolution start time could result in fewer resolutions. However, since the flights will generally be closer to each other at the time of the resolution, there may be fewer Autoresolver maneuver options (if any). This could lead to an increase in the number of losses of separation and/or greater system delay.

The effect of using a larger horizontal separation threshold for Autoresolver maneuvers was also explored. The baseline Autoresolver conflict resolution horizontal separation criterion was 7 nmi (i.e., a 2-nmi buffer added to the horizontal separation standard of 5 nmi). Only larger values of 10 and 12 nmi were evaluated because it is unlikely that a value much smaller than 7 nmi would be used in actual operations due to the range of trajectory prediction uncertainties and their respective magnitudes.[18-19] A larger horizontal conflict resolution criterion could reduce the frequency of TSAFE alerts after Autoresolver maneuvers since it should overlap the horizontal paths of both TSAFE trajectory predictions more often. However, it could also make it more difficult for Autoresolver to find conflict-free resolutions, which could increase the number of conflicts that are not resolved.

## IV. Conflict Detection Analysis

TSAFE and Autoresolver conflict detection algorithms differ in a number of ways, including number and types of trajectory predictions per flight, separation parameters, and time frames (see Table 1). These differences lead to cases where TSAFE and Autoresolver had concurrent conflict predictions but with different predicted times to initial LOS. The effect on controllers and/or pilots (if any) depends on the specific concept of operations and interface and human factors considerations that are beyond the scope of this study. Still, it is worthwhile to analyze the conflict prediction differences because they can provide insight into the precursors of interoperability issues such as when a resolution maneuver by one algorithm is followed up by an alert (and resolution) by the other.

This section contains an analysis of the baseline simulation where no resolutions were issued by either algorithm. The main metric is just the difference of the predicted times to LOS by Autoresolver and TSAFE. By definition, no TSAFE missed alert or false alert cases were analyzed since this metric requires concurrent conflict predictions by both algorithms for the same conflict pair. Since there were no trajectory prediction uncertainties, the Autoresolver-predicted time to LOS was also the actual time to LOS and served as the reference:

$$t_{error} = t_{TSAFE} - t_{AR} \tag{2}$$

A conflict pair can have many conflict predictions, though, because both Autoresolver and TSAFE continually perform conflict detection and no resolutions were issued to separate aircraft. As such, only the maximum difference (positive or negative) for each unique conflict pair over the course of the entire simulation is presented in Figure 1. First, note that most of the errors were negative, which means that the TSAFE-predicted time to LOS was generally shorter than the Autoresolver-predicted time to LOS (i.e., the actual time to LOS). This was expected since TSAFE makes four comparisons between the FP-based and DR trajectory predictions of both flights and only reports the one

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with the shortest predicted time to LOS. By comparison, Autoresolver utilizes a single flight plan-based trajectory prediction per flight during conflict detection.

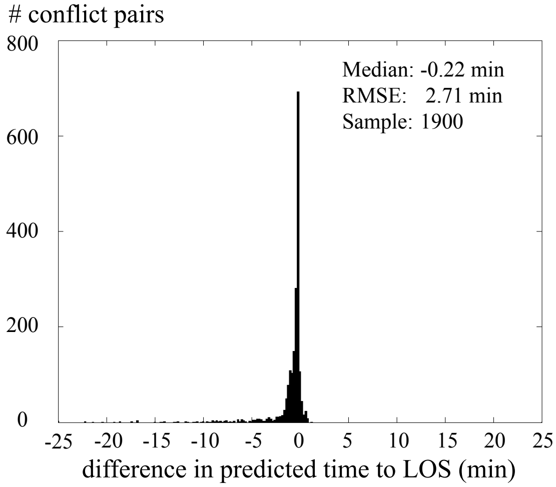

**Figure 1. Differences between TSAFE and Autoresolver predictions of time to LOS.**

A closer investigation of the cases on the far left side of the distribution (i.e., where the predicted time to LOS by TSAFE was shorter compared to Autoresolver) found that many involved flight pairs that that were flying in-trail on nearly identical headings (i.e., difference of 0.5 degrees or less). Figure 2 is a plot of the latitude and longitude of the conflict pair that had the largest negative difference between the TSAFE- and Autoresolver-predicted times to LOS. The dots are the positions of the flights at the time of the conflict predictions. Both were cruising level at 31,000 ft with an initial horizontal separation of 5.17 nmi. The flight in front (dashed gray line) was flying faster than the one behind it (solid black line), so Autoresolver did not predict that a conflict was imminent between these two flights. By comparison, TSAFE predicted that LOS had already occurred because: 1) its horizontal detection criterion for in-trail cases was 5.2 nmi, and 2) its aircraft performance models had airspeeds of 444 kts for the lead flight and 469 kts for the trailing flight (i.e., overtake situation).

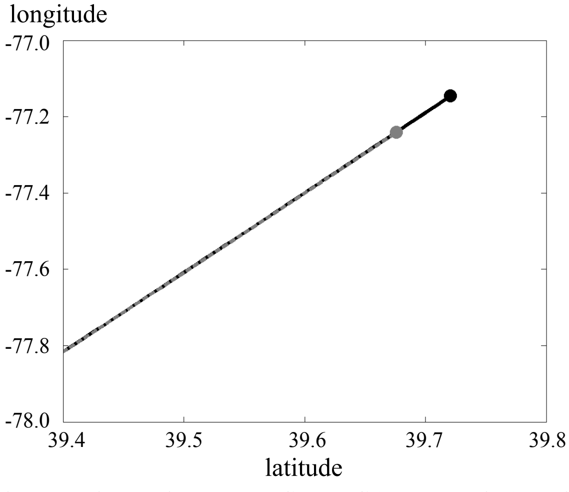

**Figure 2. Conflict pair with predicted time to LOS by TSAFE that is 25 minutes shorter compared to Autoresolver.**

It is interesting to note that there were also cases where TSAFE had a predicted time to LOS that was longer than Autoresolver. One case at the far right end of the distribution is illustrated in Figure 3. It involved one flight that was cruising at 31,000 ft (solid black line) but was close to its top-of-descent (TOD) point and a climbing flight at just under 28,000 ft (dashed gray line). TSAFE incorrectly predicted that the ascending flight would lose separation with the level flight in about 140 seconds once the former climbed above 30,000 ft because TSAFE was unaware that the

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level flight was going to descend until about 20 seconds prior to TOD. By comparison, since Autoresolver had error-free trajectory predictions for both flights including perfect knowledge of the level flight's TOD point, it correctly predicted that the two flights would lose separation in 65 seconds.

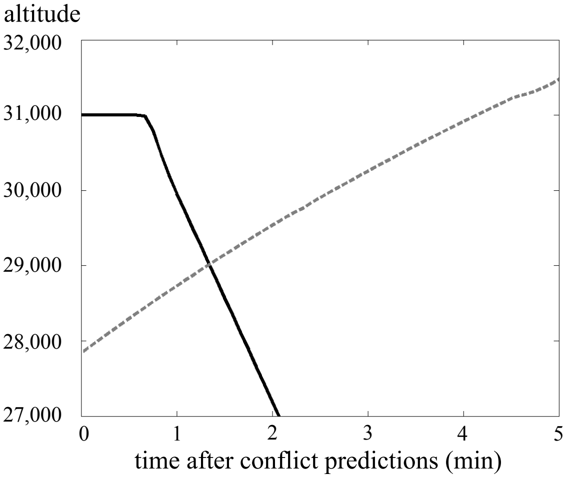

**Figure 3. Conflict pair with predicted time to LOS by TSAFE that is 75 seconds longer compared to Autoresolver.**

The predicted times to LOS by Autoresolver and TSAFE differed by 1 minute or less in 80% of the conflict pairs in this simulation, but 7.7% of conflicts had at least one discrepancy of 3 minutes or more. Figure 4 is a plot of the distribution of the phases of flight of these conflict pairs (climb (C), level (L), or descent (D)). About 80% of these cases had at least one flight in transition, with most involving either two descending flights (D/D) or two climbing flights (C/C). This result was expected because TSAFE uses an altitude envelope defined by fast- and slow-vertical rates for climbing and descending flights. A closer investigation of the cases involving two level flights (L/L) found that most were in-trail or shallow-angle conflicts with slow closure rates similar to the example plotted in Figure 2.

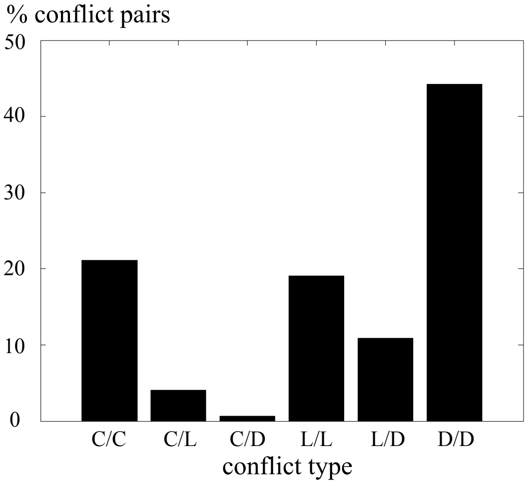

**Figure 4. Distribution of conflict types for cases where the TSAFE-predicted time to LOS differed from Autoresolver by at least 3 minutes.**

## V. TSAFE Interoperability with Autoresolver Conflict Resolutions

The interoperability of Autoresolver conflict resolution and TSAFE was evaluated in this section based on a set of fast-time simulations. Only Autoresolver issued conflict resolution maneuvers to keep aircraft safely separated, although TSAFE still performed conflict detection at all times. The interoperability metric used is the percentage of Autoresolver maneuvers that were followed up by a TSAFE alert for the same conflict pair or the maneuvered flight. Any resolutions issued by TSAFE will disrupt the implementation of preceding Autoresolver maneuvers. As such, it

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is important to measure the frequency of these cases, determine the extent to which adjusting Autoresolver conflict resolution parameters (see Table 4) can mitigate this issue, and evaluate their respective tradeoffs in terms of both safety (number of LOS) and efficiency (number of Autoresolver resolutions, delay in minutes, and fuel burn). These cases were categorized based on whether or not there was a TSAFE conflict prediction (within 24 seconds) prior to when Autoresolver issued a maneuver. If there was a TSAFE alert beforehand, then Autoresolver did not resolve the conflict from TSAFE's perspective. Otherwise, the Autoresolver maneuver actually initiated a new conflict situation according to TSAFE.

This section begins with an analysis of interoperability in the baseline simulation using the baseline Autoresolver parameters. Following that are evaluations of the effect of shorter and longer Autoresolver conflict resolution start times and larger conflict resolution separation criteria.

### A. Baseline Autoresolver Conflict Resolution Parameters

The baseline Autoresolver conflict resolution configuration utilized a start time of 8 minutes, which prohibited Autoresolver from issuing maneuvers to conflicts whose predicted time to LOS was greater than 8 minutes. Recall that these maneuvers also had to maintain at least 7 nmi of horizontal separation or 1000 ft of vertical separation for a minimum of 12 minutes.

Figure 5 is a plot of the percentage of Autoresolver maneuvers that were followed up by a TSAFE alert for the same conflict pair as a function of the amount of time after they were issued. It starts off at about 0.9% and declines to 0.5% before rising to 0.7% (solid black line). In general, these cases were split evenly between those that had a TSAFE alert both before and after the Autoresolver maneuver was issued (dashed black line) and those that only had an alert afterward (dashed gray line). Recall that the former are cases where Autoresolver did not resolve the conflict while the latter are cases where Autoresolver actually initiated new conflicts according to TSAFE.

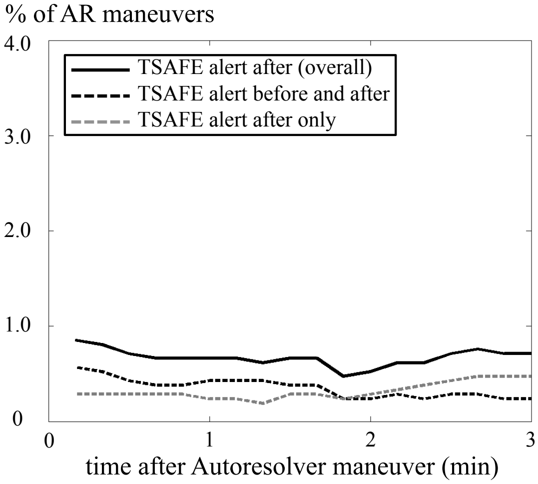

**Figure 5. Frequency of TSAFE alerts for the conflict pair addressed by Autoresolver (baseline).**

These metrics do not monotonically decrease as a function of time because there were conflict situations (i.e., aircraft geometries, types of Autoresolver maneuvers, etc.) where TSAFE did not make an alert immediately after Autoresolver issued a resolution but did so later on. For instance, the case illustrated in Figure 6 involved one flight that was holding a temporary altitude of 26,000 ft (solid black line) and about to resume climbing to its initial flight plan altitude of 35,000 ft, and a climbing flight that was just above 19,000 ft (dashed gray line) when Autoresolver commanded it to level off temporarily at 26,000 ft. Autoresolver did so because it knew that the level flight would ascend and maintain at least 1000 ft of separation at all times. By comparison, TSAFE did not have this information and, thus, predicted a conflict between these two flights based on its fast-climb trajectory prediction for the climbing flight. Actually, TSAFE is currently unable to store and utilize this data even if it were provided earlier. To prevent this type of situation, TSAFE may need to add this capability and/or Autoresolver may have to utilize buffers in the vertical dimension on top of the standard 1000 ft separation standard that was used in this simulation.

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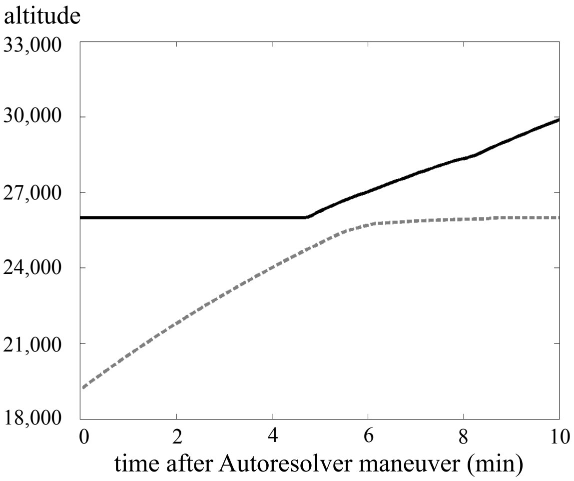

**Figure 6. Case where asymmetric knowledge results in an Autoresolver maneuver that is followed by a TSAFE alert.**

Figure 7 is a similar plot of the percentage of Autoresolver resolutions that were followed by a TSAFE alert but for the flight that was maneuvered (rather than the conflict pair being addressed by Autoresolver). The solid black line is the overall percentage and starts off at about 1.8% and declines to about 1.2% as the Autoresolver maneuvers take effect before creeping up to 2.1% as the maneuvered flight encounters other flights in the simulation.

One interesting observation about Figure 7 is that there were at least twice as many cases where an Autoresolver maneuver initiated a new conflict situation (dashed gray line) compared to cases where it did not resolve the original conflict situation (dashed black line) from TSAFE's perspective. This implies that Autoresolver resolutions for the maneuvered flight are conflict-free for the primary conflict pair more often than for secondary conflicts with other flights. By comparison, in the analysis of the conflict pair addressed by Autoresolver (see Figure 5), the cases were more evenly split between the two categories. As such, increasing the required horizontal and/or vertical separation criteria for Autoresolver maneuvers may be required to reduce the frequency of these undesirable situations.

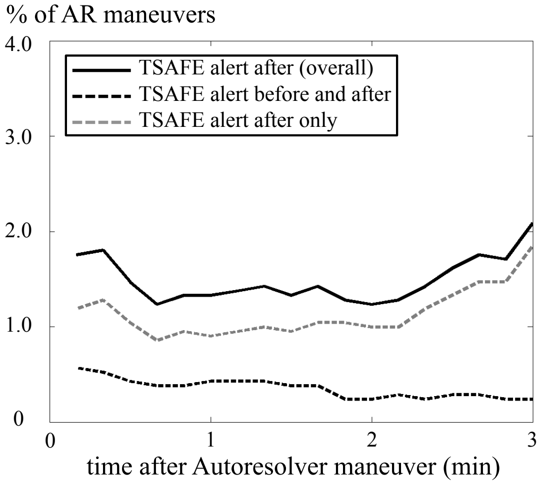

**Figure 7. Frequency of TSAFE alerts for the flight maneuvered by Autoresolver (baseline).**

### B. Analysis of Different Autoresolver Conflict Resolution Start Times

The baseline version of Autoresolver did not issue resolution maneuvers for conflict pairs whose predicted time to LOS was greater than 8 minutes. A longer Autoresolver conflict resolution start time could reduce the likelihood of a follow-up TSAFE alert (and resolution) because there would be more maneuver options and greater separation between flights (in general).

Figure 8 is a plot of the percentage of Autoresolver maneuvers that had a follow-up TSAFE alert for the conflict pair that the former was trying to resolve as a function of the amount of time after the resolution was issued. It was

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highest in the 5-minute case and lowest in the 12-minute case with the results for the baseline 8-minute case in the middle at all times. Similar behavior was also observed for the flights that Autoresolver maneuvered (see Figure 9). These results confirm the hypothesis that increasing the predicted time to LOS threshold below which Autoresolver can issue maneuvers does improve its interoperability with TSAFE. In fact, doing so maintains or improves system safety and efficiency as well.

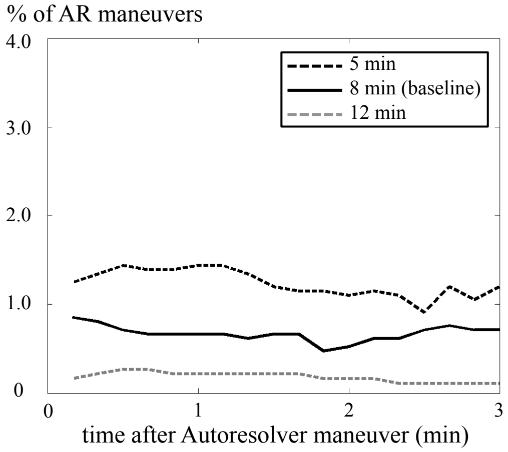

**Figure 8. Frequency of TSAFE alerts for the conflict pair addressed by Autoresolver for different resolution start times.**

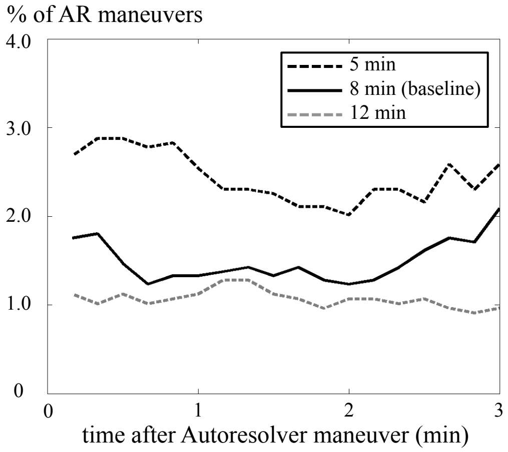

**Figure 9. Frequency of TSAFE alerts for the flight maneuvered by Autoresolver for different resolution start times.**

The main safety metric in this study is the number of LOS, which is defined as an event where two flights have less than 5 nmi of horizontal separation and less than 1000 ft of vertical separation. No LOS were observed in any of these simulations. This was somewhat expected since there were no trajectory prediction uncertainties present when Autoresolver performed CD&R. However, it is notable that Autoresolver always found a conflict-free resolution, even when it was prohibited from issuing maneuvers until the predicted time to LOS was 5 minutes or less and there were fewer conflict-free maneuver options and less separation between flights (in general). While these simulations contained thousands of flights and conflicts, they did not necessarily model the full range of conflict situations that occur in actual operations, especially since there were no trajectory prediction uncertainties. In future work, a larger traffic data set will be used and realistic trajectory prediction uncertainties will be modeled to verify these results.

As shown in Table 5, the number of Autoresolver resolutions sent out was about the same in the 5- and 8-minute cases but 11% less in the 12-minute case. In addition, while there was slightly more delay per resolution in the 12-minute case, there was actually less delay overall since fewer resolutions were issued. Similar trends were observed for fuel burn and fuel burn per resolution. Combined with the improvement in interoperability observed in the prior section, these results indicate that the Autoresolver conflict resolution start time should be set to a value greater than

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the baseline of 8 minutes. This recommendation is tentative pending follow-up simulations with realistic trajectory prediction uncertainties that will make Autoresolver maneuvers less effective, especially at longer predicted times to LOS.

**Table 5 Safety and Efficiency Metrics for Different Autoresolver Conflict Resolution Start Times**

| Performance Metric | 5 min | 8 min (baseline) | 12 min |
|---|---|---|---|
| Number of LOS | 0 | 0 | 0 |
| Number of Autoresolver Resolutions | 2087 | 2109 | 1875 |
| Delay (minutes) | 1302 | 1218 | 1176 |
| Delay per Resolution (minutes) | 0.62 | 0.58 | 0.63 |
| Fuel Burn (lbs) | 125503 | 126929 | 123007 |
| Fuel Burn per Resolution (lbs) | 60.1 | 60.2 | 65.6 |

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### C. Analysis of Different Autoresolver Conflict Resolution Horizontal Separation Criteria

The effect of using larger Autoresolver conflict resolution horizontal separation criteria on interoperability with TSAFE was also explored. Recall that the baseline Autoresolver utilized a value of 7 nmi. Since it is unlikely that a value much smaller than this would be used in actual operations due to trajectory prediction uncertainty, only larger values of 10 and 12 nmi were evaluated.

Figure 10a is a plot of the percentage of Autoresolver maneuvers that were followed up by a TSAFE alert for the same conflict pair as a function of the amount of time after the resolution was sent out. This metric was roughly the same for all three Autoresolver conflict resolution horizontal separation values. Similar behavior was observed for the flights that were maneuvered by Autoresolver (see Figure 10b). If anything, the frequency of TSAFE alerts after an Autoresolver maneuver was lowest most often when the baseline 7-nmi threshold was used.

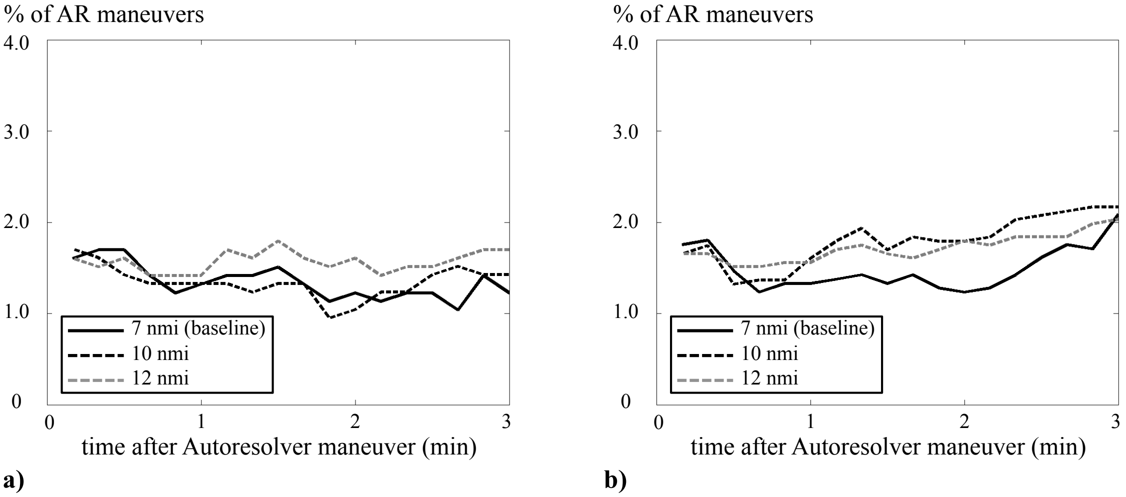

**Figure 10. Frequency of TSAFE alerts for a) the conflict pair addressed by Autoresolver, or b) the flight maneuvered by Autoresolver using different horizontal separation criteria.**

There were no LOS in any of these simulations, but there were more resolutions and greater delay and fuel burn when larger Autoresolver horizontal separation thresholds were used (see Table 6). Based on these results, there is no compelling reason to use a larger horizontal separation criterion for Autoresolver conflict resolutions. However, increasing the vertical separation threshold may still improve Autoresolver-TSAFE interoperability and should be explored in future work since the latter algorithm utilizes an altitude envelope that is defined by the fast-and slow-vertical rates in BADA when performing CD&R for climbing and descending flights.

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**Table 6 Safety and Efficiency Metrics for Different Autoresolver Conflict Resolution Horizontal Separation Criteria**

| Performance Metric | 7 nmi (baseline) | 10 nmi | 12 nmi |
|---|---|---|---|
| Number of LOS | 0 | 0 | 0 |
| Number of Autoresolver Resolutions | 2109 | 2121 | 2118 |
| Delay (minutes) | 1218 | 1266 | 1291 |
| Delay per Resolution (minutes) | 0.58 | 0.60 | 0.61 |
| Fuel Burn (lbs) | 126929 | 129510 | 135172 |
| Fuel Burn per Resolution (lbs) | 60.2 | 61.0 | 63.8 |

# VI. Future Work

Increasing the maximum predicted time to LOS at which Autoresolver was able to issue maneuvers improved its interoperability with TSAFE, but larger Autoresolver conflict resolution horizontal separation criteria had little to no effect. As such, follow-up work on Autoresolver vertical detection buffers during climb and descent is also needed. However, as discussed in this section, it is also essential to investigate the extent to which interoperability could be improved by adjusting the baseline TSAFE CD&R parameters. Following that is a description of ways to improve interoperability through tighter coupling of specific aspects of Autoresolver and TSAFE. Lastly, the importance of incorporating realistic trajectory prediction uncertainties into future simulations is also discussed.

## A. TSAFE Configuration Parameters

This paper only investigated the improvements to Autoresolver-TSAFE interoperability that could be achieved by modifying two Autoresolver conflict resolution parameters. However, TSAFE CD&R parameters could also be adjusted. Tables 7 and 8 contain the most relevant TSAFE conflict detection and resolution parameters, respectively, and their baseline values that should be explored in follow-up parametric studies where the baseline Autoresolver parameters are used and only TSAFE parameters are changed. In addition to finding the optimal combination of configurations for Autoresolver and TSAFE, tighter coupling between these two algorithms may also be necessary.

**Table 7 Baseline TSAFE Conflict Detection Parameters**

| Parameter | Baseline Value |
|---|---|
| Maximum Prediction Time Horizon (all trajectories) | 3 min |
| Maximum Prediction Time Horizon (in transition) | 2.5 min |
| Maximum FP-Based Horizontal Path Prediction Time | 3 min |
| Maximum FP-Based Altitude Prediction Time | 1.5 min |
| Maximum FP-Based Altitude Prediction Time (in transition) | 2 min |
| Maximum DR Horizontal Path Prediction Time | 2 min |
| Maximum DR Altitude Prediction Time (all flights) | 3 min |
| Maximum DR Altitude Prediction Time (in transition) | 1.5 min |
| Separation Ratio Threshold | 1.1 (i.e., 5.5 nmi horizontally and 1100 ft vertically for flights in transition or 1000 ft otherwise) |

**Table 8 Baseline TSAFE Conflict Resolution Parameters**

| Parameter | Baseline Value |
|---|---|
| Action Start Time | 2 min |
| Conflict-Free Time | 3 min |
| Separation Ratio Threshold | 1.4 (i.e., 7.0 nmi horizontally and 1400 ft vertically for flights in transition or 1000 ft otherwise) |

## B. Increased Coupling between Autoresolver and TSAFE

This study has shown that additional coordination between Autoresolver and TSAFE is needed to improve their interoperability. Loose coupling can include guidelines about how to set Autoresolver parameters based on TSAFE's configuration (and/or vice versa) using the results of this paper and the additional parametric studies described in the

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previous section. If this is insufficient, tighter coupling might also be necessary and could involve having TSAFE check potential Autoresolver maneuvers for conflicts before being issued (and/or vice versa), which should reduce the frequency of TSAFE alerts after an Autoresolver maneuver (and/or vice versa).

Although a higher level of coordination between Autoresolver and TSAFE can improve their synergy and overall effectiveness in maintaining safe separation between aircraft, the spirit of the fundamental AAC principle that these two systems act as independent safety layers must be maintained. For example, a common trajectory predictor must not be used because any inherent weaknesses will affect the performance of both Autoresolver and TSAFE, possibly leading to conflict situations that neither system can detect and resolve. Also, when determining the optimal degree of coordination between Autoresolver and TSAFE and the specific parameters used, it is important to model realistic trajectory prediction uncertainties.

### C. Trajectory Prediction Uncertainty

No trajectory prediction uncertainties were present in any of the simulations conducted in this study. As a result, Autoresolver's conflict predictions and resolutions were both error-free, which enabled it to maintain safe separation between all aircraft. Although the zero-uncertainty simulations revealed several interoperability issues and principles for Autoresolver and TSAFE, identifying the more subtle ones and verifying the findings of this study requires that realistic trajectory prediction uncertainties be incorporated into future simulations in order to model the full breadth and variety of conflict situations that occur in the NAS.

## VII. Conclusions

This study utilized fast-time simulations to evaluate the interoperability of Autoresolver and TSAFE in terms of the frequency of conflict resolution maneuvers by the former that were followed up by a conflict prediction by the latter. About one percent of Autoresolver maneuvers had a subsequent TSAFE alert for the same conflict pair and about two percent for the maneuvered flight. These situations are undesirable since they disrupt the implementation of Autoresolver maneuvers by controllers and/or pilots. Increasing the maximum predicted time to loss of separation at which Autoresolver could issue maneuvers from the baseline eight minutes to 12 minutes decreased the frequency of these cases by at least half and reduced delay and fuel burn while maintaining zero losses of separation. However, larger Autoresolver conflict resolution horizontal separation criteria had little effect, which is not surprising because TSAFE uses both flight plan-based and dead-reckoning trajectory predictions for all flights during conflict detection in addition to an altitude envelope defined by fast and slow vertical rates for flights in transition. These results must be verified in follow-up work using larger traffic files and realistic trajectory prediction uncertainties to evaluate the combined Autoresolver-TSAFE system with the full range of conflict situations that are present in actual operations.

In summary, the interoperability principles for Autoresolver and TSAFE that were derived in this study are:

- TSAFE must be informed about climb and descent clearances as early as possible.
- TSAFE must be enhanced to incorporate information about future clearances into trajectory predictions.
- Autoresolver should be allowed to issue resolutions at greater predicted times to loss of separation.

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