

PILOT ACCEPTANCE, COMPLIANCE, AND PERFORMANCE WITH AN AIRBORNE CONFLICT MANAGEMENT TOOLSET

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A human-in-the-loop experiment was conducted at the NASA Ames and Langley Research Centers, investigating the En Route Free Maneuvering component of a future air traffic management concept termed Distributed Air/Ground Traffic Management (DAG-TM). NASA Langley test subject pilots used the Autonomous Operations Planner (AOP) airborne toolset to detect and resolve traffic conflicts, interacting with subject pilots and air traffic controllers at NASA Ames. Experimental results are presented, focusing on conflict resolution maneuver choices, AOP resolution guidance acceptability, and performance metrics. Based on these results, suggestions are made to further improve the AOP interface and functionality.

Introduction

In today's air transportation business environment, aircraft operators are increasingly looking for means to increase flight efficiency. However, with air travel demand once again rising to levels that exacerbate delays and challenge the capacity of the National Airspace System (FAA, 2004), large efficiency improvements may be difficult to realize under current operational conditions. As a result, it has been acknowledged that a transformational, rather than evolutionary, approach to air traffic management modernization is needed (DOT, 2004).

As part of the Advanced Air Transportation Technologies project, NASA has developed such a far-term, transformational concept, called Distributed Air/Ground Traffic Management (DAG-TM) (NASA, 1999). The goals of DAG-TM are to increase efficiency and maintain safety through a redistribution of decision-making authority among airborne and ground-based elements of the air transportation system. It is a gate-to-gate concept, addressing all flight phases from dispatch to arrival.

En Route Free Maneuvering

En Route Free Maneuvering is one component of DAG-TM, addressing the en route and terminal-transition phases of flight. In an En Route Free Maneuvering environment, trained crews of equipped aircraft assume responsibility for traffic separation. Such crews would be free to modify their flight path in real time, without approval from an air traffic controller, as long as basic flow management initiatives are complied with (e.g., crossing a terminal airspace entry point at a specified time). These flights would operate under a new set of flight rules called Autonomous Flight Rules (AFR).

Except for busy terminal areas, where AFR operations would not be permitted, AFR traffic would be integrated with Instrument Flight Rules (IFR) traffic. AFR flight crews would be responsible for separation from both IFR and other AFR aircraft. Air traffic controllers would issue flow management constraints to all aircraft, and continue to provide separation among IFR aircraft, accommodating those operators who choose not to equip for AFR. By distributing separation assurance among multiple airborne and ground-based elements in this way, the National Airspace System may be able to absorb a higher increase in demand beyond what is possible with a centralized, ground-based approach.

Background

Previous Research

The work presented in this paper builds upon previous studies conducted at NASA as well as initial Free Flight research by organizations such as NLR in the Netherlands (Hoekstra et al., 2000). Past NASA experiments investigated such topics as AFR operations in confined airspace and the use of aircraft intent for decision making (Krishnamurthy et al., 2003).

The Autonomous Operations Planner

Central to AFR operations are the capabilities of airborne conflict prevention, detection, and resolution, as well as adherence to traffic flow management constraints. It is assumed that pilots cannot safely perform these functions without some form of decision support. As such, NASA Langley Research Center has developed a prototype airborne toolset called the Autonomous Operations Planner (AOP) (Barhydt & Krishnamurthy, 2004).

The prototype AOP interface is designed around a modern “glass cockpit” flight deck. It provides conflict alerts and resolution guidance via the navigation display, using state and intent data from the ownship and proximate traffic. To meet flow constraints, it also generates conflict-free paths that achieve Required Times of Arrival (RTAs) at waypoints. The AOP has been developed using a human-centered approach, with resolution guidance complementing the pilot’s choice of control mode. For example, when the aircraft is being flown in a tactical mode (e.g., a selected heading or altitude) or when very near-term conflicts exist, resolution guidance is presented as a simple heading or vertical speed command. When the aircraft is flown in a strategic mode (i.e., coupled to the aircraft’s flight management system (FMS)), resolution guidance is presented as an FMS route modification.

Conflicts are displayed by highlighting the intruder aircraft and indicating the region of conflict along the active flight path with a colored “dog bone.” The AOP also provides information to help pilots avoid inadvertently creating new conflicts while maneuvering. These conflict prevention tools take on two forms: Maneuver Restriction Bands and Provisional Conflict Alerts. Maneuver Restriction Bands are displayed as “no fly” heading and vertical speed ranges. Using a “dashed dog bone” symbology, Provisional Conflict Alerts show regions of conflict along *proposed* flight paths (e.g., a modified but unexecuted FMS route or a selected but unengaged heading). Figure 1 shows an example of AOP symbology on a Boeing 777-style navigation display.

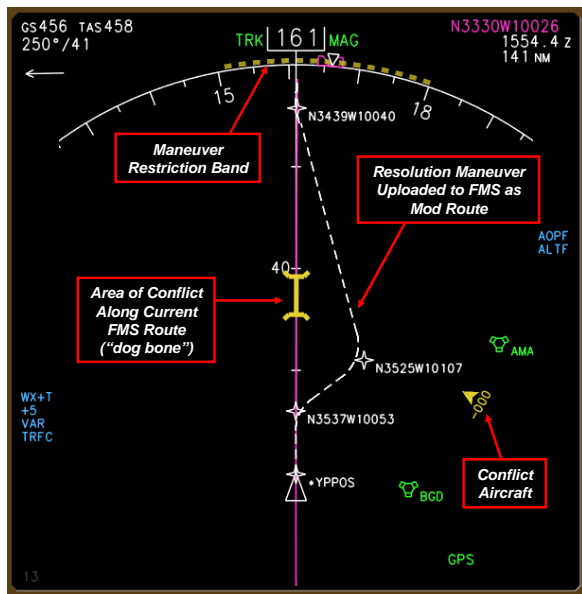


Figure 1. AOP Interface with Strategic Resolution

Experimental Approach

In summer 2004, the NASA Ames and Langley Research Centers jointly conducted a human-in-the-loop simulation of En Route Free Maneuvering operations (Barhydt & Kopardekar, 2005). This experiment extended the previous research in several ways. A realistic, mixed AFR-IFR operating environment was simulated, including overflight aircraft as well as arrivals. The AOP was enhanced to provide vertical resolution guidance in addition to lateral guidance. In addition, interactions with ground-based air traffic controllers were studied.

This paper presents a subset of the En Route Free Maneuvering experimental results, focusing on conflict resolution maneuver choices, pilot-reported acceptability of AOP guidance, and performance metrics, including how pilot compliance with AOP affected resolution performance.

Participants

Test subjects included 12 pilots at NASA Langley as well as pilots and air traffic controllers at NASA Ames. The NASA Langley subject pilots were all Airline Transport Pilot rated with experience in Boeing glass cockpit aircraft. These pilots flew workstation-based flight simulators that emulated the displays of an AOP-equipped Boeing 777. Additional AFR and IFR background traffic was supplied with pseudo-pilot stations staffed by research personnel.

Figure 2 shows the experimental airspace. It consisted of simulated high- and low-altitude sectors of a portion of Fort Worth Center. The sectors were staffed at NASA Ames by five FAA-qualified air traffic controllers. They provided separation services between IFR aircraft and were given automated tools for conflict detection and resolution. In addition, researchers acted as pseudo-controllers in large “ghost” sectors surrounding the experimental sectors, providing limited services to flights entering and exiting the subject-controlled airspace.

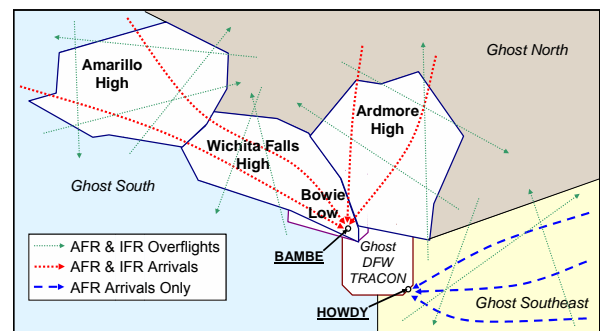


Figure 2. Experimental Airspace

Scenario Design

The experiment was designed in a within-subjects format, with 16 different scenarios. Four different traffic conditions were simulated, which varied the amount of traffic as well as the relative proportions of AFR and IFR overflight aircraft. Table 1 details the four traffic conditions.

Table 1. Traffic Conditions Tested

Condition	Avg. Traffic Density	% IFR	% AFR
C1	slightly above current Monitor Alert parameter	100%	0%
C2	equal to C1 density	75%	25%
C3	$\approx 1.5 \times$ C1 density	50%	50%
C4	$\approx 2 \times$ C1 density	35%	65%

At each of the four traffic conditions, pilots flew two overflight profiles and two arrival profiles. Except for C1 scenarios (in which all flights were IFR), subject pilots were responsible for resolving scripted and unscripted traffic conflicts. AOP alerted pilots to conflicts up to 10 minutes prior to predicted Loss of Separation (LOS). Pilots were trained to use AOP strategic resolution guidance, tactical resolution guidance, and (in the case of manual maneuvers) conflict prevention information as appropriate to the situation. They were also instructed to operate the aircraft as they would during line operations. Although hand-flying was not available, pilots were allowed to use any desired autopilot modes, including both FMS-coupled modes and tactical modes.

Results & Discussion

The NASA Langley subject pilots encountered a total of 500 traffic conflicts throughout the 12 AFR scenarios (C2, C3, and C4). For 332 of these conflicts, the subject pilot performed a resolution maneuver. The analyses presented below show results for these conflicts, without distinguishing between traffic conditions. The effects of traffic density on resolution performance are treated in a separate publication (Doble, Barhydt, & Hitt, 2005).

AOP Compliance

To examine the effects of AOP resolution maneuver compliance on resolution performance, resolution maneuvers were divided into six categories, based upon whether the maneuver was strategic or tactical and whether or not the pilot followed AOP guidance. These categories are summarized in Table 2. Two different performance metrics were then used to evaluate the maneuvers: induced conflicts and conflicts requiring multiple resolution maneuvers.

Table 2. Resolution Compliance Categories

Category	Description	Count
Strategic Comply	Pilot implements AOP-recommended route modification without modifications	141
Strategic Noncomply	Pilot edits waypoints before implementing AOP-recommended route modification	0
Strategic Manual	Pilot ignores or does not seek AOP resolution, and manually edits waypoints, altitudes, etc. of FMS active route	15
Tactical Comply	Pilot maneuvers in direction of AOP-recommended heading or vertical speed	118
Tactical Noncomply	Pilot maneuvers away from AOP-recommended heading or vertical speed	15
Tactical Manual	AOP tactical guidance not available, pilot implements own lateral or vertical maneuver via autopilot mode control panel	43

Induced Conflicts. The frequency of induced conflicts is a measure of the ability of pilots and AOP to account for aircraft other than the intruder when calculating a resolution maneuver. An induced conflict was defined as a new conflict arising within one minute of a previous resolution maneuver and directly caused by that maneuver. Figure 3 shows the percentage of resolutions inducing a conflict in each of the six compliance categories. Results from χ^2 tests indicate no significant differences in the frequency of induced conflicts across the three tactical categories ($\chi^2(2, N = 176) = 0.27, p > 0.05$), but a significantly higher frequency of induced conflicts for Strategic Manual maneuvers vs. Strategic Comply maneuvers ($\chi^2(1, N = 156) = 32.2, p < 0.05$).

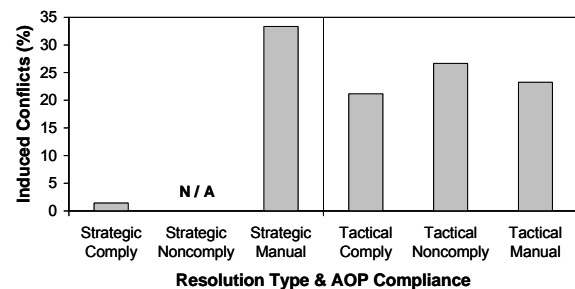


Figure 3. Induced Conflicts vs. AOP Compliance

The lowest induced conflict rates occurred when pilots followed AOP guidance. This highlights the advantage of decision support when resolving conflicts involving multiple proximate aircraft. It is conjectured that the relatively high rate of induced conflicts among tactical maneuvers was due primarily to two factors: the time to predicted LOS when the maneuvers were executed, and the characteristics of the AOP tactical resolution algorithm. During the experiment, tactical resolution

maneuvers were generally initiated closer to predicted LOS than strategic maneuvers. In such situations, especially in the high-density airspace simulated in this experiment, some induced conflicts may be inherently unavoidable, as the first priority is usually to resolve the most critical conflict in a timely manner. In addition, for very near-term conflicts (under 2 minutes to LOS), the AOP tactical resolution algorithm did not take other aircraft into account when calculating resolution guidance. This algorithm was chosen for its ability to successfully resolve complicated conflict situations without the need for maneuver coordination between aircraft (Eby, 1994). Ongoing research will investigate the integration of this algorithm with the AOP conflict prevention tools in order to further reduce induced conflicts.

While the significant increase in induced conflicts for Strategic Manual resolutions is cause for concern, it should be noted that three of these five induced conflicts were caused by the same pilot during the same scenario. Nevertheless, pilot training and the AOP conflict prevention symbology may warrant further attention as these subject pilots all implemented route modifications despite being shown Provisional Conflict Alerts.

Multiple Resolutions. The frequency of multiple resolutions is a measure of the ability of pilots and AOP to resolve a conflict and remain out of conflict. If a subject pilot was in conflict with the same intruder multiple times and implemented more than one resolution maneuver, this was noted as a multiple resolution conflict. Figure 4 shows the percentage of conflicts requiring multiple resolutions in each compliance category. Results from χ^2 tests indicate no significant differences in the frequency of multiple resolutions across the strategic categories ($\chi^2(1, N = 156) = 1.67, p > 0.05$). The differences among tactical categories were significant ($\chi^2(2, N = 176) = 6.04, p < 0.05$).

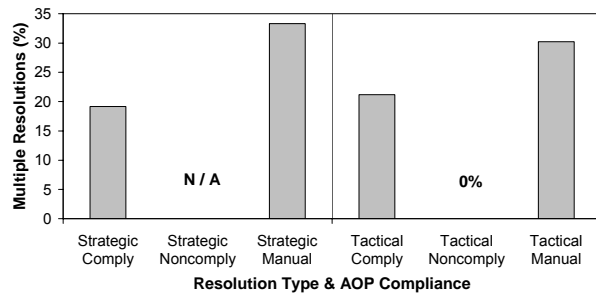


Figure 4. Multiple Resolutions vs. AOP Compliance

The lower multiple resolution rate for maneuvers that complied with AOP guidance (vs. manual maneuvers) shows the benefits of decision support when resolving conflicts between aircraft flying complex, four-dimensional trajectories. While the lowest multiple resolution rate occurred when pilots did not follow AOP guidance (Tactical Noncomply), this is not seen as a cause for concern. Compliance only accounted for 3% of the variance in multiple resolutions, and this category of maneuvers had a relatively small sample size. In addition, there may have been a performance tradeoff, with these maneuvers effectively avoiding the intruder aircraft at the expense of additional induced conflicts.

Choice of Maneuver Axis

To judge the relative effectiveness of lateral and vertical AOP guidance, the maneuvers categorized above as Strategic Comply and Tactical Comply were further separated into Strategic Lateral, Strategic Vertical, Tactical Lateral, and Tactical Vertical categories.

Induced Conflicts. Figure 5 shows the percentage of induced conflicts that occurred for each of the four axis categories. Results from χ^2 tests indicate no significant differences between either the strategic categories ($\chi^2(1, N = 141) = 0.46, p > 0.05$) or the tactical categories ($\chi^2(1, N = 118) = 0.37, p > 0.05$). For the reasons mentioned above, it is not surprising that strategic resolutions resulted in fewer induced conflicts than tactical resolutions, but within the strategic and tactical categories, the choice of maneuver axis appears to have had little effect.

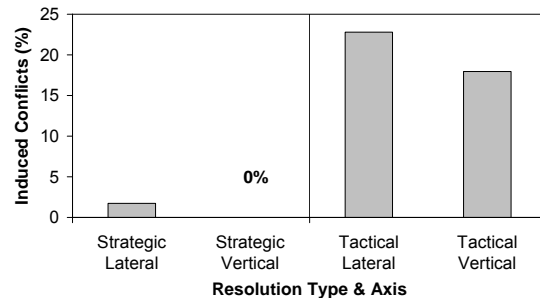


Figure 5. Induced Conflicts vs. Maneuver Axis (When AOP Complied With)

Multiple Resolutions. Figure 6 shows the percentage of multiple resolutions that occurred for each of the four maneuver axis categories. Results from χ^2 tests indicate no significant differences between either the two strategic categories ($\chi^2(1, N = 141) = 1.24, p > 0.05$) or the two tactical categories ($\chi^2(1, N = 118) = 0.02, p > 0.05$). This shows that lateral and vertical

maneuvers were similarly effective in preventing multiple resolutions. However, the slightly higher incidence of multiple resolutions for Strategic Vertical maneuvers is worth noting. These maneuvers required pilots to adjust the autopilot altitude value in addition to uploading an FMS route modification. There were cases when the altitude value was not properly adjusted and the aircraft failed to follow the resolution maneuver. Compounding this was the difficulty of displaying vertical path changes on a horizontal situation display. Ongoing research will investigate other options for presenting vertical maneuver information, including the use of vertical situation displays.

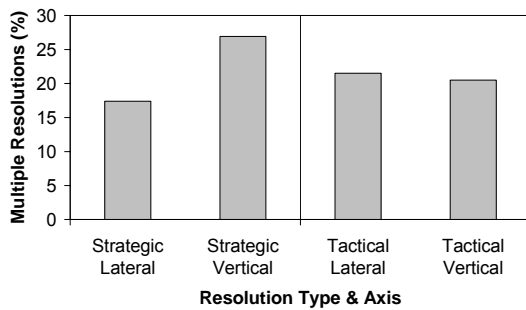


Figure 6. Multiple Resolutions vs. Maneuver Axis (When AOP Complied With)

Acceptability of AOP Resolution Guidance

To examine factors that affect pilot perception of the acceptability of AOP resolution guidance, subject pilots were asked after each scenario to rate, on a 1 to 7 scale, the acceptability of a) the first AOP strategic resolution in the scenario, and b) AOP tactical resolutions in general during the scenario. A series of correlations was then performed to determine if relationships existed between resolution acceptability and four other factors: conflict duration, maneuver axis (lateral or vertical), multiple resolutions, and induced conflicts. These results are presented in Table 3. Overall resolution acceptability was high for both strategic resolutions ($M = 6.31$, $SD = 1.28$) and tactical resolutions ($M = 5.12$, $SD = 1.60$).

Table 3. Resolution Acceptability

Attribute	Acceptability Correlation		Test
	Strategic Resolutions (N = 109)	Tactical Resolutions (N = 135)	
Conflict Duration	-0.24*	0.02	Pearson
Maneuver Axis	-0.18	0.10	Point-biserial
Multiple Resolution	-0.39*	0.14	Point-biserial
Induced Conflict	-0.02	-0.17*	Point-biserial

* = significant correlation at $p < 0.05$ level

The acceptability of AOP strategic resolution maneuvers was significantly correlated with conflict duration and multiple resolutions. The significance of conflict duration agrees with comments provided during debrief sessions, which indicated that pilots were frustrated by AOP computation delays and the options available when AOP was unable to calculate a solution. While the AOP strategic resolution algorithm (a genetic algorithm) normally converged on a solution within one second, insufficient feedback may have been provided to pilots when computation times were longer, creating the appearance that AOP had “frozen up.” The significant correlation with multiple resolutions is also reasonable, as one of the primary benefits of intent-based, strategic decision support is that the necessity for multiple resolution maneuvers should be reduced by accounting for trajectory changes that would be unknown to a solely state-based system.

The acceptability of AOP tactical resolutions was only significantly correlated with whether or not the resolution induced a conflict. As mentioned above, depending on the time to predicted LOS, the AOP tactical guidance may or may not have accounted for aircraft other than the intruder. As such, there were cases when the tactical guidance disagreed with Maneuver Restriction Bands. Although this behavior was explained to subject pilots during training exercises, this is recognized as a significant human factors issue. Research is underway to modify the AOP near-term tactical resolution logic so that conflicting information is not presented to pilots.

Practice Effects

The En Route Free Maneuvering experiment lasted a total of eight days, with three days devoted to training, four days for data collection, and one day for debriefing. Each data collection day included four scenarios, with one at each traffic condition, and with the order of conditions varying across days.

To identify any learning or practice effects, conflicts were sorted by day and evaluated with the same performance metrics presented above. Figure 7 shows the frequency of induced conflicts and multiple resolutions across days. χ^2 tests indicate that no significant differences in the frequency of induced conflicts ($\chi^2(3, N = 332) = 1.37$, $p > 0.05$) or in the frequency of multiple resolutions ($\chi^2(3, N = 332) = 4.78$, $p > 0.05$) existed across the four days.

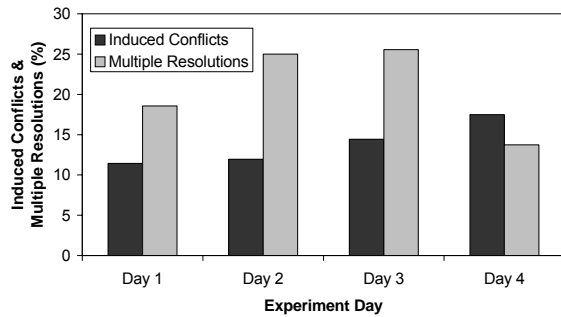


Figure 7. Resolution Performance by Day

While no significant practice effects were found, it is interesting to compare the performance by day with the resolution maneuvers chosen. Figure 8 shows the percentage of maneuver types chosen each day. Notionally, resolution performance appears to degrade with increases in manual and non-complying maneuvers over the first three days of the experiment, then improve on Day 4 with an increase in Strategic Comply maneuvers.

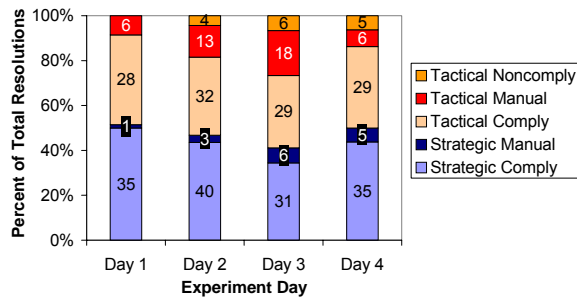


Figure 8. Resolution Maneuver Compliance by Day

Conclusions

Through the above analysis of conflict resolution maneuvers, several conclusions can be drawn about the performance of pilots during AOP-equipped AFR operations. First, the choice of maneuver axis (lateral or vertical) had little effect on resolution performance, indicating that resolution maneuvers can be well-executed in either axis. Second, resolution performance was shown to generally improve when pilots complied with AOP-recommended resolution maneuvers. Finally, although pilot acceptability of AOP guidance was high overall, possible ways to further increase acceptability and performance were identified. These methods include better integration of AOP near-term tactical resolution logic with conflict prevention information, improved feedback when AOP cannot converge on a strategic solution, and the potential inclusion of a vertical situation display. Along with previous findings, these results further support the

feasibility of the En Route Free Maneuvering concept while highlighting areas for future research.

Acknowledgements

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