Pilot and Controller Evaluations of Separation Function Allocation in Air Traffic Management

10th USA/Europe Seminar on Air Traffic Management Research and Development

Chicago, IL, USA

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Technical Challenge and Objective

• Creating scalable system through “function allocation” of separation assurance
  – Eliminate human workload as a growth-limiting factor
  – Greater role for automation
  – Greater role for aircraft

• Paradigm shifts for ground and aircraft operations
  – Both approaches have significant implementation risk
  – Pursue both avenues and make compatible

• Motivation: 15+ years research on air and ground concepts for increasing capacity indicate powerful function allocation solutions
  – Autonomous Flight Rules (AFR)
    Distributed air/ground concept with self-separation-equipped operators
  – Advanced Airspace Concept (AAC)
    Trajectory-based concept with datacom-equipped IFR operators

• Objective: enable mixed operations (not segregation)
  – Open airspace for all is key for user benefits
  – Provides largest range of viable operations for aviation community

• Approach: coordinated human-in-the-loop air/ground experiments
  – Homogeneous operations (completed 2010)
  – Mixed Operations
Separation Concepts

Ground-Based Automated Separation

- Automation increasingly used for primary separation
- Data link to send trajectory instructions to equipped aircraft
- Controller manages automation, airspace

Airborne Self-Separation

- Airborne surveillance
- Avionics-integrated automation for self-separation
- Pilot selects/executes maneuvers approved by automation
Mixed Operations

- **Air Traffic Control (ATC) role**
  - Separate IFR from IFR
  - Not responsible for AFR or AFR-IFR separation
  - Coordinate with AFR (voice) on IFR maneuvers near AFR

- **AFR role**
  - Separate from all traffic
  - Apply right-of-way with AFRs
  - Give right-of-way to all IFRs
  - Coordinate with ATC (voice) on short-notice conflict resolution maneuvers
Key Research Issues for Mixed Operations

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These four issues were investigated in two coordinated Human-In-The-Loop experiments
Common Test Airspace and Configurations

- **Controller-focused experiment configuration**
  5 sectors, 2 areas, 2 ghost sectors
  8 single-pilot stations (AFR/IFR)
  8 pseudo-pilot stations (IFR)
  *Subjects*: 7 FAA front line managers

- **Pilot-focused experiment configuration**
  2 sectors (49, 59), 1 ghost sector
  6 “team” stations (AFR crew)
  3 pseudo pilot stations (IFR)
  *Subjects*: 17 airline flight crews

Cleveland Center (ZOB)
High altitude (FL 330 and above)
Separation Automation & Human Interface

Ground-Based Automation System

- Integrated display, functionality, & data link
- Automatic strategic & tactical conflict management
- Automated routine operations (handoffs, transfer of comm.)
- HMI designed for management by exception
- Accessibility to conflict info, resolution tools, trial plan tools, timelines
- Interactive via keyboard entry, data tags, trackball

MACS (Multi Aircraft Control Simulation)
High-fidelity display/control emulations for controllers, supervisors, pseudo-pilots
Separation Automation & Human Interface

Airborne Automation System

- Integrated with avionics
- Traffic separation in strategic and tactical flight modes
- Route optimization integrated with de-confliction
- Conformance with trajectory constraints
- Provisional probing for conflict-free trajectory changes
- Implicit coordination with traffic aircraft actions

ASTOR (Aircraft Simulation for Traffic Operations Research)
High-fidelity displays, controls, performance of modern Boeing-style jet
## Key Research Issues for Mixed Operations

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# Controller-Focused Experiment Matrix

<table>
<thead>
<tr>
<th>Air/ground function allocation</th>
<th>Tu, We</th>
<th>Th, Fr</th>
<th>Mo, Tu</th>
<th>We, Th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed IFR/AFR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground IFR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>Minimum NextGen</td>
<td>Moderate NextGen</td>
<td>Maximum NextGen</td>
<td></td>
</tr>
<tr>
<td>Human/automation function allocation</td>
<td>NextGen Maturation Level of automation increases</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# NextGen Maturation

<table>
<thead>
<tr>
<th>NextGen (NG) Level</th>
<th>Baseline</th>
<th>Minimum</th>
<th>Moderate</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller's role</td>
<td>IFR separation</td>
<td>IFR separation</td>
<td>IFR separation</td>
<td>Exceptions only (IFR)</td>
</tr>
<tr>
<td>Automation's role</td>
<td>Non-critical ATC support</td>
<td>Non-critical ATC support</td>
<td>Critical ATC support</td>
<td>IFR separation, critical ATC support</td>
</tr>
<tr>
<td>Automation capabilities</td>
<td>Conflict list</td>
<td>Conflict list</td>
<td>Plus trial planner; strategic resolver</td>
<td>Plus tactical resolver</td>
</tr>
<tr>
<td>IFR trajectory clearances</td>
<td>Voice</td>
<td>Voice</td>
<td>Voice / Datacom</td>
<td>Datacom</td>
</tr>
<tr>
<td>IFR frequency changes</td>
<td>Voice</td>
<td>Voice / Datacom</td>
<td>Voice / Datacom</td>
<td>Datacom</td>
</tr>
<tr>
<td>AFR frequency changes</td>
<td>Voice</td>
<td>Datacom</td>
<td>Datacom</td>
<td>Datacom</td>
</tr>
<tr>
<td>AFR access to IFR intent</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ATC access to AFR intent</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Traffic density</td>
<td>1x</td>
<td>1.2x</td>
<td>1.5x</td>
<td>2x</td>
</tr>
</tbody>
</table>

Human/Automation function allocation

NextGen Maturation

Level of automation increases →
Loss of Separation (LOS) Events

- Each data point represents 120 minutes of simulation time across five test sectors
- Half attributed to automation failures causing late conflict detections
- Half attributed to operator/automation interaction failures
- No statistically significant differences between IFR-only and Mixed IFR/AFR in each NextGen stage

<table>
<thead>
<tr>
<th>Traffic level</th>
<th>Monitor Alert Parameter</th>
<th>Data comm eq.</th>
<th>LOS IFR-only</th>
<th>LOS Mixed IFR/AFR all (AFR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>1x</td>
<td>18</td>
<td>0%</td>
<td>1</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.2x</td>
<td>22</td>
<td>25%</td>
<td>3</td>
</tr>
<tr>
<td>Moderate</td>
<td>1.5x</td>
<td>27</td>
<td>50%</td>
<td>10</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.0x</td>
<td>36</td>
<td>100%</td>
<td>0</td>
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Loss of Separation: <5 nm lateral and <800 feet vertical
Controller Real-time Workload Ratings

- Workload assessment tool, 6-point scale, gathered every 3 minutes
- No statistically significant differences between IFR-only and Mixed IFR/AFR
- Lowest workload in Maximum NextGen (“Max-NG”) condition
Controller Acceptability Rating Scale (CARS), administered post-run

- Over all 8 conditions: 84% rated “acceptable”, 16% rated “less than acceptable”
- Some compensation required by controllers for smooth operations
- Mixed IFR/AFR operations rated same or slightly higher than IFR-only
- Lower mean rating in Moderate NextGen (“Mod-NG”) affected by late conflict detections
Controller Situation Awareness Ratings

- Situation Awareness Rating Tool (SART), administered post-run
- Highest situation awareness in Maximum NextGen (“Max-NG”)
  - Perceived by controllers differently
  - Low demand, more spare capacity, higher understanding
- No statistically significant differences between IFR-only and IFR/AFR mixed operations
• Flight progress compared on similar routes after 20 minutes flight time
• More AFR maneuvering (less progress) expected to resolve AFR-IFR conflicts
  – IFR had 50/50 chance of being maneuvered for conflicts
• Baseline, Minimum NextGen (“Min-NG”), and Moderate NextGen (“Mod-NG”)
  – Less intent availability and/or reliability
• Maximum NextGen (“Max-NG”)
  – Similar efficiency when intent available
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### Experiment Matrix: Part 1

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<tr>
<th>Factors</th>
<th>Values</th>
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<tbody>
<tr>
<td>Time to Buffer Loss</td>
<td>&lt; 20 sec.</td>
</tr>
<tr>
<td></td>
<td>20-60 sec.</td>
</tr>
<tr>
<td></td>
<td>1-2 min.</td>
</tr>
<tr>
<td></td>
<td>2-4 min.</td>
</tr>
<tr>
<td></td>
<td>4-10 min.</td>
</tr>
<tr>
<td>Encounter Angle</td>
<td>Acute (0-50 deg.)</td>
</tr>
<tr>
<td></td>
<td>Obtuse (130-180 deg.)</td>
</tr>
<tr>
<td>Maneuver Dimension</td>
<td>Lateral encounter</td>
</tr>
<tr>
<td></td>
<td>Vertical encounter</td>
</tr>
<tr>
<td>Passage Orientation</td>
<td>Intruder passes in front</td>
</tr>
<tr>
<td></td>
<td>Intruder passes behind</td>
</tr>
</tbody>
</table>

24 total conflicts tested, 10 minute runs,

Fractional [4]x[2x2x2] between-subjects design (12 conflicts per crew)
LOS Events (AFR-IFR)

<table>
<thead>
<tr>
<th>Initial Alert Time</th>
<th>Losses of Separation</th>
<th>Number of Runs</th>
</tr>
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<tbody>
<tr>
<td>4 – 10 minutes</td>
<td>0</td>
<td>33</td>
</tr>
<tr>
<td>2 – 4 minutes</td>
<td>0</td>
<td>32</td>
</tr>
<tr>
<td>1 – 2 minutes</td>
<td>0</td>
<td>46</td>
</tr>
<tr>
<td>20-60 seconds †</td>
<td>11</td>
<td>62</td>
</tr>
<tr>
<td>&lt; 20 seconds</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>11</strong></td>
<td><strong>188</strong></td>
</tr>
</tbody>
</table>

† Excludes 3 runs in this bin with borderline loss < 0.04 nmi

- 188 conflicts analyzed with varied initial alert time and conflict geometry (IFR intent not avail.)
- No LOS events for all runs with alert time > 60 seconds
- Pilot debrief comments: 5 or more minutes notice preferred
- No geometry effect evident (encounter angle, maneuver dimension, passage orientation)
Buffer Loss Events

- 3 nm safety buffer added to 5 nm lateral separation standard
  - Used by primary intent-based separation system
- Statistically significant difference between [2-10 minutes] and [1-2 minutes]
- Statistically significant effect of passage orientation
  - More effective in conflicts with intruder passing behind
- Statistically significant effect of encounter orientation
  - Suggests non-circular buffers more efficient

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</tr>
<tr>
<td>&lt; 20 seconds</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>63</strong></td>
<td><strong>174</strong></td>
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Pilot-Focused Experiment
## Experiment Matrix: Part 2

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<tr>
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<th>Values</th>
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<tbody>
<tr>
<td>IFR Intent</td>
<td>On</td>
</tr>
<tr>
<td>Availability</td>
<td>Off</td>
</tr>
</tbody>
</table>

30 minute runs, 72 total flights tested

2x1 within-subjects design
Conflicts Per Flight

- 72 flights (30 min. each), 377 total conflicts detected, no LOS
- IFR Intent ON – 18% fewer conflicts, reduced tail (fewer cases of high conflicts/flight)
- Intent sharing promotes greater stability and efficiency of trajectories
Conflicts With Initial Alerting < 4 Min.

- 111 of 377 conflicts detected as “pop-ups” (<4 minutes notice)
- IFR Intent ON: 21% fewer pop-ups, reduced number of 1-conflict flights
- Pilot procedure for pop-up conflicts is to resolve with “tactical” rather than “strategic” solution

Number of Conflicts in Tactical Mode

- Frequency
- IFR Intent OFF
- IFR Intent ON
Switching Modes: Strategic to Tactical

- 122 auto-flight mode switches made (strategic to tactical)
- IFR Intent ON: 33% fewer mode switches
- Intent sharing promotes greater stability, efficiency, and predictability of trajectories
Conclusions

• No significant differences between these types of operations
  – Separation violations, controller workload, acceptability, and situation awareness
  – Presence of a few self-separating aircraft does not impact the performance of the ground-based separation system

• Flight crews reliably provided mixed-operations separation
  – In all cases where at least one minute warning was given
  – Preference was for at least five minutes notice
  – Regardless of encounter geometry
  – Key elements are sharing intent information and air/ground coordination on unplanned maneuvers

• Maximum NextGen stage outperformed all others
  – Same level of safety as the Baseline
  – Twice the throughput and a lot less controller workload
  – Equivalent maneuver delay, while all other stages required extra AFR maneuvering
Next Steps
Expanded Analysis of Function Allocation Concepts for Separation Assurance (SA)

- Document alternative concepts
- Seek community input, involvement
- Conduct various analyses and sims
- Summarize findings, recommendations

SA Roles and Responsibilities

[Diagram showing different roles and responsibilities]

**Area of Interest**

* A wide range of concepts to be identified

**Level of Automation**

- Fully Autonomous Aircraft, Unmanned Aircraft Systems
- Fully Automated Ground-based System
- Manual SA Using Displays
- SA Decision Support Tools
- Today’s Air Traffic System Has stretched the limits of human workload capacity; cannot handle future traffic demand
- Early Free Flight Studies of Situation-Awareness-based Airborne SA

**SA Decision Support Tools**

- Manual SA Using Displays
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- Fully Automated SA

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