Flight Deck Merging and Spacing and Advanced FMS Operations

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David H. Williams
Crew Systems & Aviation Operations Branch
NASA Langley Research Center
Hampton, VA 23681-2199
(757) 864-2023
E-mail: david.h.williams@nasa.gov
Outline

• **Flight Deck Merging and Spacing**
  – Recent Langley HITL simulation testing.
  – Future plans.

• **Advanced FMS Concepts**
  – 4D FMS and temporal RNP.
Airlines are interested in fuel-saving operations called Continuous Descent Arrivals (CDA). CDAs provide a viable means to reduce noise and fuel-burn while decreasing flight time.

However...

- CDAs optimized for single aircraft performance can lead to capacity decrease.
- Adequate separation for CDA operations may require excessive vectoring at cruise altitudes.
- Conservative separation between aircraft must be imposed to minimize controller intervention.
A Solution

Manage the arrival flow of aircraft during cruise flight so they arrive adequately spaced to begin arrival procedures.

Allow crew to actively manage the spacing between themselves and their leading aircraft during arrivals.

Onboard automation, supporting appropriate procedures, allows the flight crew to make minor speed adjustments to manage their pair-wise spacing.
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This is Flight Deck-based Merging and Spacing
FDMS Development Team

• NASA has been supporting the development of Flight Deck-based Merging and Spacing since February 2005.
  – Includes FAA, UPS, MITRE, industry, and others.

• FDMS is a transitional step toward Airborne Precision Spacing and NextGen.

• UPS has started using an initial FDMS tool to perform airborne spacing with CDAs.
  – Current testing uses Eurocontrol-developed spacing tool.
  – NASA and ACSS, avionics supplier, have a Space Act Agreement that includes transferring our advanced spacing tool to them for future use.
Flight Deck Merging and Spacing Overview

<table>
<thead>
<tr>
<th>Departure</th>
<th>Terminal</th>
<th>En route</th>
<th>Terminal</th>
<th>Landing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of climb</td>
<td>ADS-B range</td>
<td>Top of descent, CDA entry, &amp; merge fix</td>
<td>CDA</td>
<td>ILS</td>
</tr>
</tbody>
</table>

Operations center-based speed advisory

Set-Up

Conduct

Termination
## Spacing Performance From Prior Testing

<table>
<thead>
<tr>
<th>Study Type</th>
<th>Spacing Mean</th>
<th>Spacing Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast-time studies of non-disruptive cases</td>
<td>&lt; 1.0 sec</td>
<td>1.8 – 4.2 sec</td>
</tr>
<tr>
<td>High-fidelity, in-trail piloted simulation</td>
<td>1.0 sec</td>
<td>1.7 sec</td>
</tr>
<tr>
<td>Medium-fidelity, merging and in-trail piloted simulation</td>
<td>0.8 sec</td>
<td>4.7 sec</td>
</tr>
<tr>
<td>Flight evaluation of in-trail spacing</td>
<td>0.8 sec</td>
<td>7.7 sec</td>
</tr>
</tbody>
</table>

### Controller Field Data

- **DTW multilateration data**<sup>a</sup>  
  27 sec

- **DFW RADAR data**<sup>b</sup>  
  19.6 sec

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<sup>a</sup> B.G. Jeddi, et al, 2<sup>nd</sup> ICRAT conference Belgrade 2006  
<sup>b</sup> M.G. Ballin, H. Erzberger, AIAA-96-3723, 1996
Flight Deck HITL Experiment


• Focused on testing procedures during off-nominal air traffic events.
  – Vectoring and speed intervention by controllers.

• 26 airline pilots and 2 confederate controllers.
  – 3 weeks with 7 PC-based simulators and one full-workload simulator.
  – 8 arrival scenarios for each group.
FDMS Sample Scenario

Spacing groups are: [12345]; [678]

Aircraft #7 is vectored off-path; #8 loses spacing guidance

Aircraft #3 has the controller issue a new speed during descent
Advanced FMS Operations

FDMS Preliminary Results

• Spacing Procedures
  – Only minor, technical errors were detected during the simulation.
  – 19 of the 26 pilots felt the procedures were complete and adequate; of
    the 7 saying ‘no’:
    • Four commented on the formatting of the checklist.
    • Two commented on the criteria to resume spacing.
      – One felt it was unclear, the other, it was too stringent.
    • One was unclear on what speed to follow when suspending spacing.
  – We feel the lack of clarity was in presentation and not in the procedure
    design.

• Spacing Performance
  – 104 flights conducted spacing to runway threshold.
    (0.6 seconds mean error with 4.6 seconds standard deviation).
  – There are still a few outliers to be analyzed.
  – An analysis of cross restriction adherence, spacing and separation at
    key waypoints is underway.

Complete experiment results will be documented in 2009 conference paper.
FDMS Future Plans

• Continued support of FAA Flight Deck-based Merging and Spacing team.
  – FDMS group is supporting the Requirements Focus Group in the Operational Performance Assessment for Enhanced Sequencing and Merging (closely related).
  – Field trial of early FDMS operations (single arrival route) planned for March 2009.
  – Application Description is being developed for the next phase of FDMS (multiple arrival routes leading to multiple runways).

• Enhancements to trajectory-based spacing tool.
  – Parallel runway operations.
  – Improve robustness when outside surveillance range and with large wind forecast errors.

• Integration with advanced FMS.
The flight management system is the heart of a modern flight deck, providing:

- Navigation
- Guidance
- Flight Planning
- Data communications

**FMS Development Time Line**

*Research focus has evolved from Core Development to Integration with Air Traffic Management to Enhanced Functionality*
NASA FMS Research Objectives

• Develop advanced FMS guidance methods for energy management in the terminal area.
  – Specifically addressing NextGen Super Density Operations (SDO).

• Develop flight crew procedures for FMS operations in the terminal area.
  – With and without advanced guidance.
  – Coordinated with Air Traffic Controller procedures.
4D-FMS Guidance and Control

- **Horizontal Guidance**:
  - Aircraft State
  - Lateral error

- **Lateral Control**:
  - Altitude, speed and energy targets

- **Vertical Control**:
  - Status and recalculation flags
  - Vertical guidance
  - Energy management
  - Time error management
  - Spacing guidance

- **Vertical Path Definition**:
  - Reference horizontal path
  - Reference vertical path

- **Trajectory Generation**:
  - Lateral path definition
  - Vertical path definition

- **Constraint Management and Relaxation**:
  - RTA time estimate

- **Additional Elements**:
  - Airplane state, guidance flags
  - Weather, time

Advanced FMS Operations
4D-FMS Time Control

JPDO candidate ConOps require different forms of time control. Current 4D-FMS Options:

- **Required Time of Arrival (RTA) Control.**
  - Iterate on 4D trajectory prediction until ETA matches RTA.
  - Fly normal 3D guidance.
  - Periodic trajectory updates assure compliance to RTA.
  - Multiple RTA waypoints may be needed.

- **Continuous Time Control.**
  - 4D trajectory generated or provided by ATC.
  - A reference “time box” follows the 4D trajectory as predicted.
  - Distance from aircraft location to time box used for speed guidance.

- **Combined RTA and Continuous Time Control.**
  - Trajectory prediction updated as needed depending on ATC requirements.
  - Continuous time control along updated trajectory.
Temporal RNP Concept

*Introduced as a straightforward extension of RNP from the cross-track (lateral) sense to the along-track (longitudinal) sense*

- Longitudinal RNP = Temporal RNP * Ground Speed
- Temporal ANP = Longitudinal ANP / Ground Speed

**Continuous 4D mode:**
Range Error = Desired range - Estimated range

**RTA mode:**
Range Error = (ETA-RTA) * Ground speed

**4D reference trajectory is recomputed when ETA exceeds RTA by the calculated time tolerance**

**Continuous 4D mode:**
Calculated time tolerance is used as the temporal RNP

RNP: Required Navigation Performance
ANP: Actual Navigation Performance
RNP Pilot Interface

Lateral, Vertical and Longitudinal (Temporal) Display of RNP/ANP

Extension to B737 NG Displays

Time Error = Range Error / Ground speed
Energy Navigation (eNAV)

- Optimized vertical trajectory includes energy profile to minimize fuel, noise and emissions.
  - Dynamically re-computed to reflect changing winds and tactical speed changes.
  - Flap/gear deployment timed to manage energy.
- Energy error guidance cue eliminates excessive throttle and speed brake usage.

eNAV has been integrated into the NASA research FMS for testing with Airspace Super Density Operations in both batch and HITL simulations.
Advanced FMS Research Plan

• Identify FMS capabilities and requirements for NextGen Super Density Operations.

• Design “adaptive” navigation and guidance concepts that enable full-time FMS operation.
  – Energy Guidance with Airborne Precision Spacing.
  – RNP RNAV with time control.
    • Lateral, vertical and temporal containment.
  – Datalink and Database lateral routing flexibility.

• Prototype and test concepts.
  – Single aircraft workstation studies using autopilot models.
  – Multi-aircraft using Air Traffic Operations Laboratory with pilot models.
  – Control law testing and validation using piloted high-fidelity simulation.

• Develop and evaluate flight crew procedures.
  – Scripted and live ATC interaction.
  – Coordinated with ground automation research studies.
Summary

• NASA has been supporting the development of Flight Deck-based Merging and Spacing since February 2005.
  – UPS has started using an initial FDMS tool to perform airborne spacing with CDAs.
  – NASA and ACSS, avionics supplier, have a Space Act Agreement that includes transferring our advanced spacing tool to them for future use.
  – Recent HITL simulation at Langley has provided insight and data on FDMS usage during off-nominal conditions.

• NASA is actively developing and evaluating advanced FMS concepts for Super Density Operations.
  – Expanded vertical and temporal RNP concepts are being explored.
  – Energy guidance concepts are being developed and evaluated for efficiency benefits and flight crew acceptance of new arrival procedures.
Pilot Feedback and Workload

Eye tracking data in the full-mission simulator showed little to no change between the dwell time and scan pattern for the primary displays and out the window between current day operations and spacing operations. NASA TLX for workload reveals no perceived difference in workload.

Acceptability of the spacing tool, heads-down time and confidence in the speed guidance were all high (greater than 6 on 7 point scale). Questionnaires from workstation simulation shows no perceived change in workload between in-trail and merging operations. Speed change count was consistent between merging and in-trail and workstation and full-mission simulations.
Stream Stability

- For spacing operations to be of use to the ATC system and provide the expected benefit, the system must be stable to long streams of spacing aircraft.
- Stability is measured by performance (achieved spacing and speed changes) invariant to stream position.
- Three studies have looked at stability:
  - 100 aircraft stream in fast-time batch
  - 40 aircraft streams in CDA fast-time batch
  - 9 aircraft streams in piloted, workstation-based simulation

No destabilizing effect has been seen
Knowledge of Final Approach Speed

Knowledge of planned final approach speed (FAS) is critical to achieving desired precision.

FAS is not currently part of the ADS-B standard message content.

Figure shows spacing at threshold for four different assumptions on FAS.
Behavior of Spacing with CDAs

**CDAs with airborne spacing**
Evaluated whether most of the benefit of CDAs can be obtained while maintaining/increasing capacity
Work in support of M&S Working Group
Scenarios were 40 arriving aircraft along 4 routes (1 en route, 2 low altitude merges) to one runway starting 350 nm out

**Results**
Can achieve high delivery precision even with limited speed authority
System behavior is stable (no effect based on location in stream and acceptable number of speed changes)
Spacing can overcome large initial spacing deviations
Schedule deviation (difference from initial times to actual) shows no ill-behavior; initial value is the difference in the first aircraft’s actual flight time and the scheduler’s prediction