Simulation Studies of Airborne Self-Separation

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FACET User Group Workshop
FAA Free Flight Program Office

Washington, DC
13 March 2003

Overview

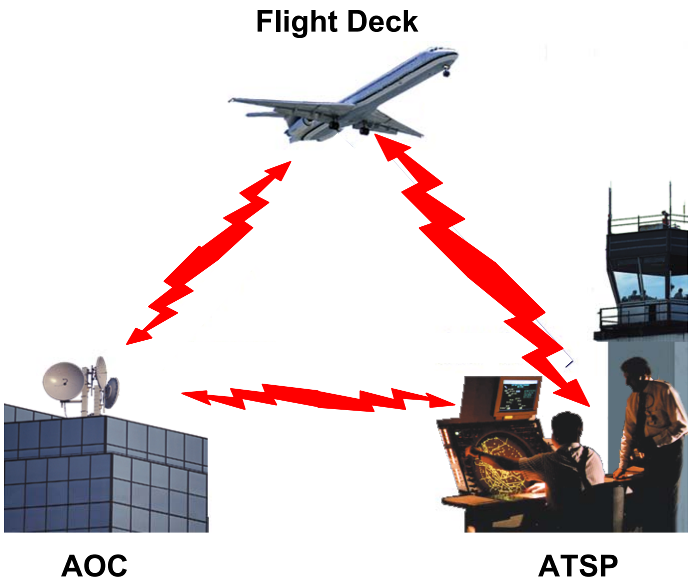
- DAG-TM concept of Free Flight operations
  - Airborne self-separation for Free Maneuvering
- Motivation for simulation experiments
  - Evaluate feasibility of airborne self-separation for Free Maneuvering
- Simulation environment – FACET
- Numerical experiments
  - Performance evaluation of airborne separation assurance for free flight
  - Agent-based approach to conflict resolution with spatial constraints
  - Properties of air traffic conflicts for free and structured routing
- Concluding remarks

DAG-TM: A "Con. Ops." for Free Flight

- Distributed Air/Ground Traffic Management (DAG-TM) is a detailed concept of operations for mature Free Flight
  - DAG-TM concept developed by a team of NASA researchers
  - Free Maneuvering is a key element of DAG-TM
  - Aircraft self-separation is necessary to enable Free Maneuvering

- Definition of DAG-TM:

  An integrated operational concept in which flight deck crews, air traffic service providers and aeronautical operational control personnel use distributed decision-making to enable user preferences and increase system capacity, while meeting ATM requirements and maintaining safety



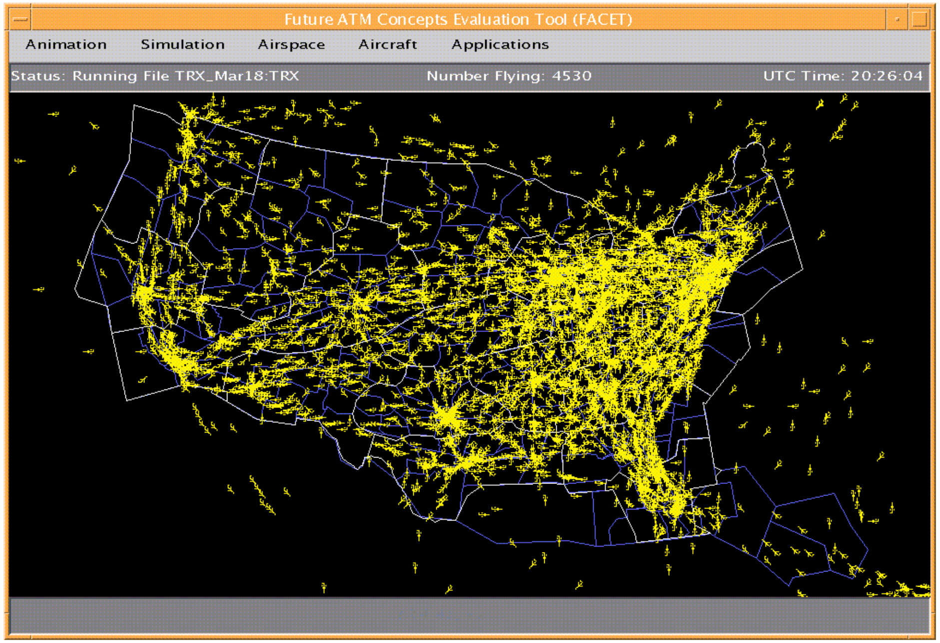
Green, S.M., Bilimoria, K.D., and Ballin, M.G., "Distributed Air/Ground Traffic Management for En Route Flight Operations," ***Air Traffic Control Quarterly*****, Vol. 9, No. 4, 2001, pp. 259–285.**

Simulation Studies

- Investigations of Free Maneuvering feasibility
  - Performance evaluation of airborne separation assurance for free flight
  - Agent-based approach to conflict resolution with spatial constraints
  - Properties of air traffic conflicts for free and structured routing
- Initial feasibility evaluation studies
  - Focus on system-level performance characteristics and issues
  - No human in the loop
  - Perfect information
- Simulations conducted using FACET
  - Scenarios derived from real traffic data

FACET: Future ATM Concepts Evaluation Tool

- Simulation tool for exploring advanced ATM concepts
  - Developed at NASA-Ames



- Airspace Modeling (over contiguous U.S.)
  - Center/sector boundaries
  - Jet/Victor airways
  - Navigation aids
  - Airports

- Trajectory Modeling
  - Fly flight-plan routes or direct (great circle) routes over round earth
  - Climb/descent performance models
  - Dynamic models for turns and acceleration/deceleration

Bilimoria, K.D., Sridhar, B., Chatterji, G.B., Sheth, K.S., and Grabbe, S.R., "FACET: Future ATM Concepts Evaluation Tool," ***Air Traffic Control Quarterly*****, Vol. 9, No. 1, 2001, pp. 1–20.**

Study #1

Performance Evaluation of Airborne Separation Assurance for Free Flight

Karl Bilimoria, Kapil Sheth, Hilda Lee, and Shon Grabbe
Paper No. 2000-4269
AIAA Guidance, Navigation, and Control Conference
Denver, CO
August 2000

Problem Definition

- Research Objectives:
  - Study feasibility of airborne separation assurance for free flight
  - Develop techniques to assess performance of CD&R algorithms

- Approach
  - Use two qualitatively different CD&R methods
    - » Geometric Optimization approach
    - » Modified Potential-Field approach
  - Create a Free Flight traffic scenario
    - » Utilize initial conditions obtained from real traffic data
  - Evaluate system performance using metrics
    - » Reliability
    - » Efficiency
    - » Stability

Free Flight Traffic Scenario

- Birth points extracted from Enhanced Traffic Management System (ETMS) data
  - 3 hours of data for Denver Center, from 9 am – 12 noon, on 18 March 1999
  - 955 aircraft in Class A airspace (≥ FL180)

- Free Flight simulation
  - Fly direct route from birth point to destination (great circle navigation)
  - Deviate from nominal trajectory as necessary for conflict resolution
  - Conflict resolutions shared equally
  - Horizontal flight only
    - » Aircraft cruise at their appropriate altitudes

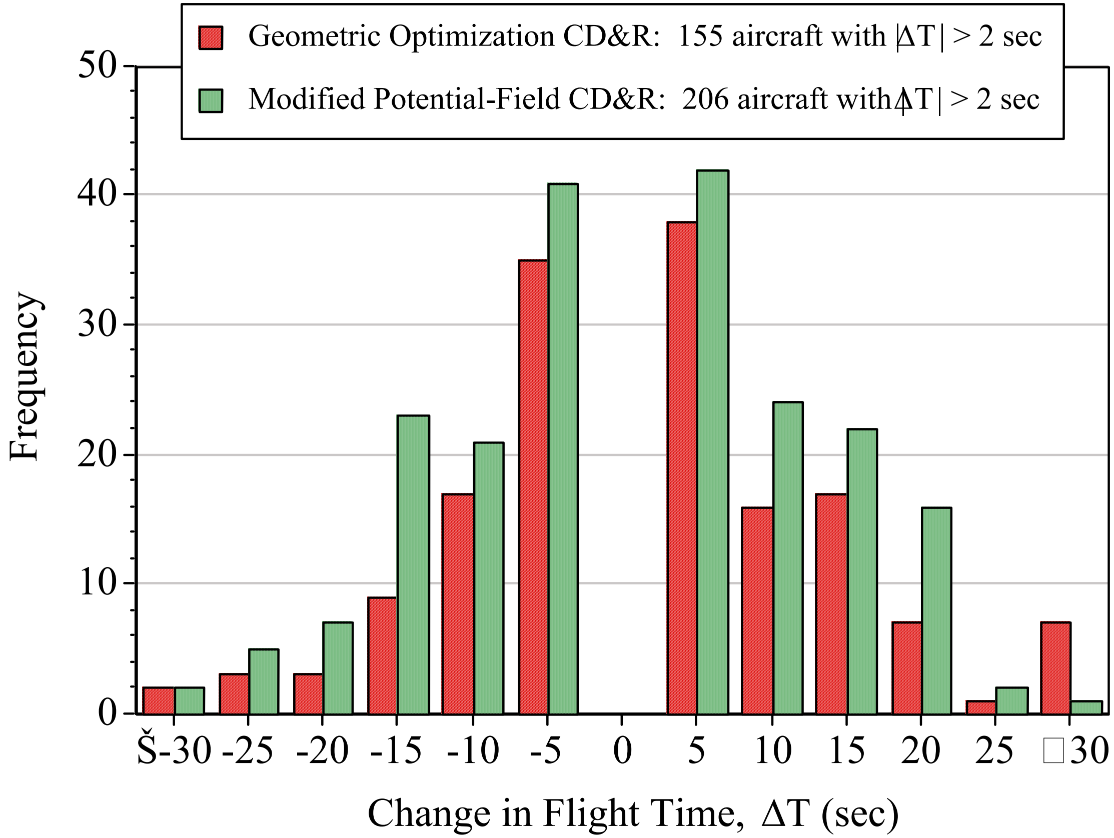
Metrics for Performance Evaluation

- Reliability
  - Absence of any separation loss in simulation (with CD&R engaged)

- Efficiency
  - Incremental cost of conflict resolution, measured by:
    - Change in path length (relative to nominal trajectory with no CD&R)
    - Change in flight time (relative to nominal trajectory with no CD&R)

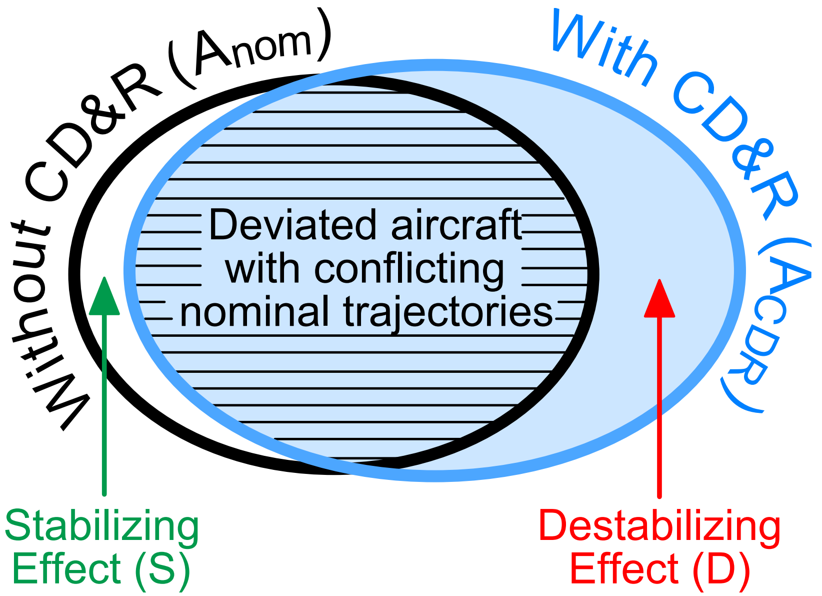
- Stability
  - Conflict resolution often creates new conflicts – “domino effect”
    - Number of deviated aircraft that were not nominally in conflict – destabilizing effect
    - Number of aircraft, nominally in conflict, that were not deviated – stabilizing effect

Efficiency Results: Flight-Time Changes



	Geometric Optimization CD&R Method	Modified Potential-Field CD&R Method
Count for $\lvert \Delta T \rvert$	155 aircraft	206 aircraft
Sgn. Mean	6 sec	2 sec
Abs. Mean	12 sec	11 sec
Abs. Sum	1810 sec	2226 sec

Stability Results



Domino Effect Parameter

$$DEP = \left\lfloor \left(\frac{D}{A_{nom}}\right) - \left(\frac{S}{A_{nom}}\right) \right\rfloor = \left(\frac{D-S}{A_{nom}}\right)$$

	Geometric Optimization CD&R Method	**Modified Potential-Field CD&R Method**
A_{nom}	209	209
A_{CDR}	248	352
D	47	145
S	8	2
DEP	**0.19**	**0.68**

Summary of Study #1

- Investigated feasibility of self-separation using a Free Flight traffic scenario constructed from real air traffic data
- All conflicts were resolved
- Deviations of individual trajectories were very small
  - Flight-time changes ~10 sec (nominal flight time ~ 90 min)
  - Path-length changes ~1 nm (nominal path length ~ 650 nm)
- Impact on system stability is dependent on CR method
  - Percentage of additional aircraft drawn into conflicts ~ 20% to 70%
- These preliminary results support the feasibility of airborne separation assurance for Free Flight

Study #2

An Agent-Based Approach to Aircraft Conflict Resolution with Spatial Constraints

Karen Harper, Sean Guarino, Mark Hanson, Karl Bilimoria, and Daniel Mulfinger

Paper No. 2002-4552

AIAA Guidance, Navigation, and Control Conference

Monterey, CA

August 2002

Problem Definition

- Research Issue:

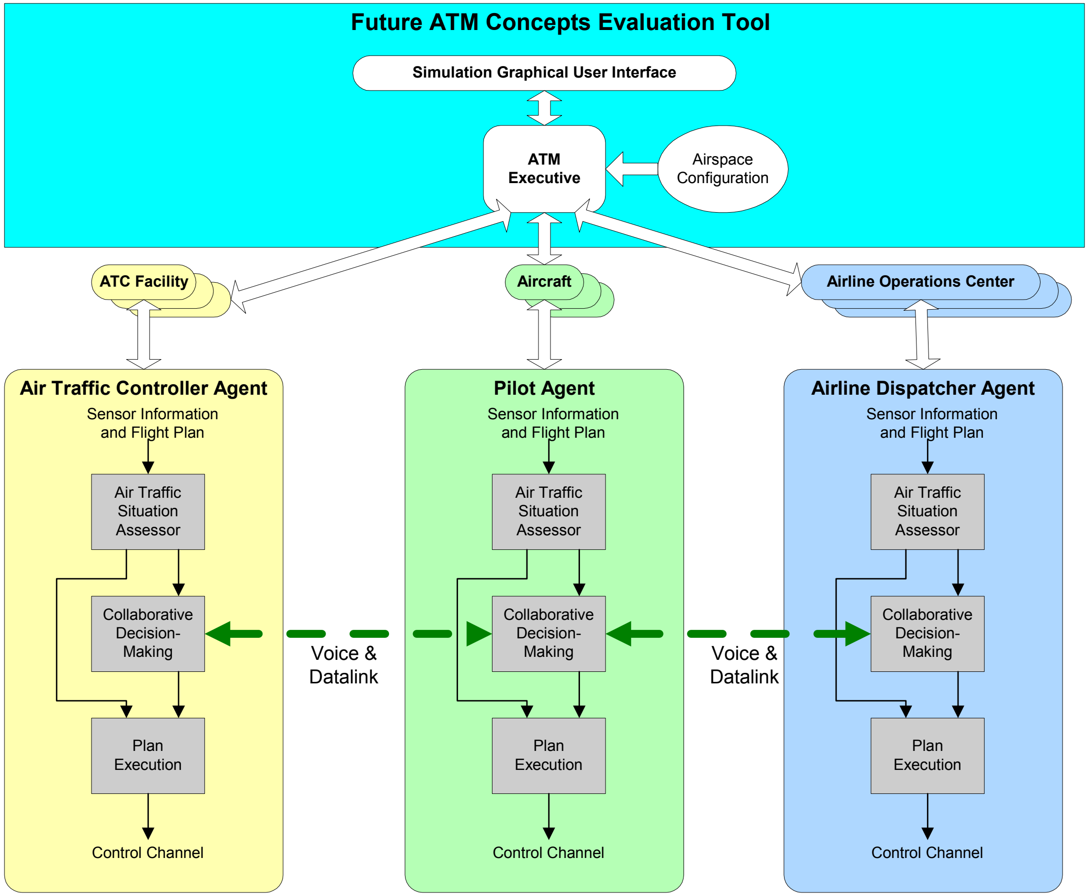
  In realistic ATM operations, how often will the need arise for multiple decision-makers to conduct complex negotiations to resolve potential conflicts with aircraft and/or airspace?

- Approach
  - Implement a set of ATM agent behaviors, procedures, and protocols to evaluate the feasibility of airborne self-separation with spatial constraints
    - » Agent decisions based on "Principled Negotiation"
  - Generate free flight scenario with realistic air traffic patterns and restricted airspace constraints
  - Run agent-based models through scenario, and monitor trajectory deviations arising from conflict resolution maneuvers
    - » Conflicts resolved with "even split" in trajectory deviations could have been solved by autonomous (fully decentralized) CD&R algorithms
    - » Conflicts resolved with uneven split required negotiation (or some form of coordinated decision-making between 2 or more agents)

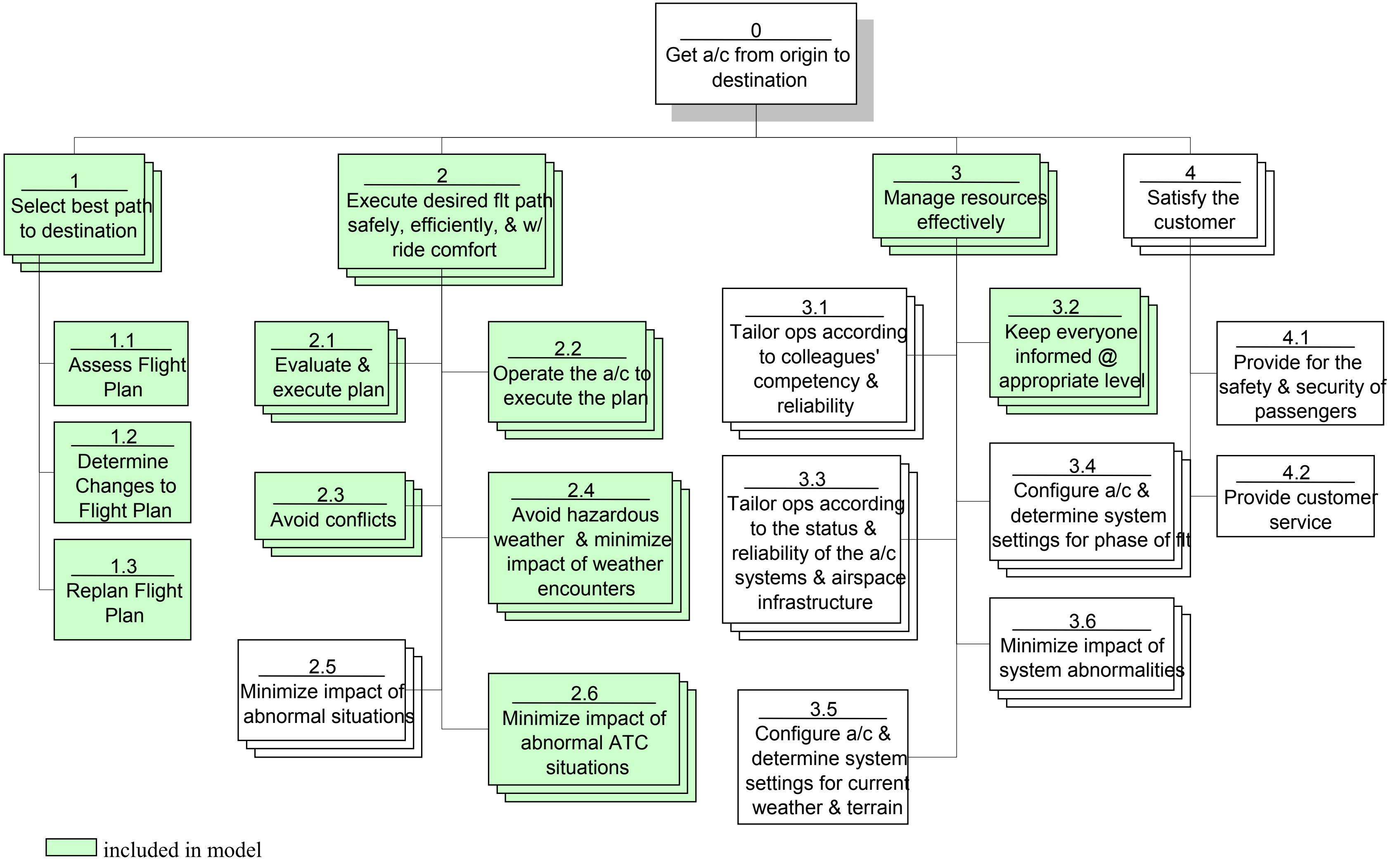
Modeling of Agents in the ATM System

Functions of key agents:

- Pilot and Air Traffic Controller
  - Traffic conflict detection
  - Airspace conflict detection
  - Conflict prioritization
- Airline Dispatcher
  - Weather
  - Legality/safety
- Collaborative decision-making for conflict resolution and airspace hazard avoidance
  - Traffic conflict resolution via geometric optimization
  - Restricted airspace avoidance



Pilot Agent Model



Simulation

- Free Flight simulation based on real data for L.A. Center (ZLA)
  - Simulation limited to horizontal flight

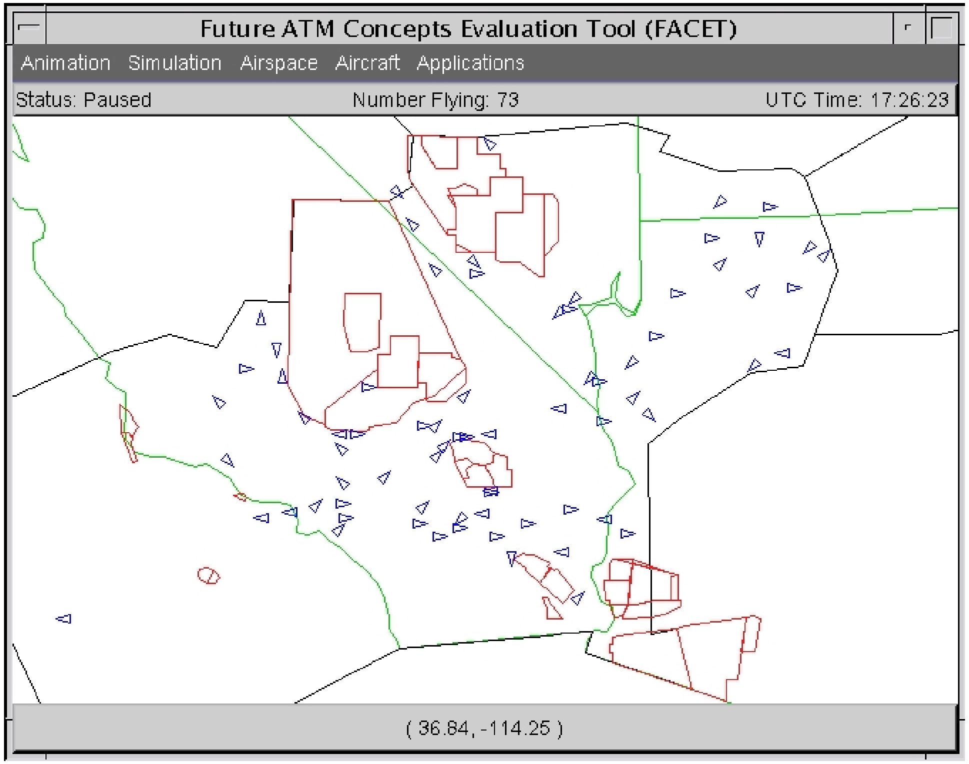
- Traffic Data
  - 4 hours of ETMS data: 8 am – 12 noon, on 06 Sep 2001
  - Total of 955 aircraft flew in high-altitude ZLA airspace (at or above FL290)
  - Birth points extracted from ETMS data

- Special Use Airspace (SUA) Data
  - Spatial boundaries from National Flight Data Center (NFDC) database
  - Activation/deactivation times from Planned Daily Utilization data, obtained from U.S. en route high-altitude IFR charts
  - 32 Restricted Airspace areas in ZLA airspace, at or above FL290

- Aircraft fly directly from their birth points to destinations in FACET simulation, deviating only as necessary to avoid conflicts with aircraft and/or SUAs

Results

- Nominal trajectories with avoidance functionality OFF
  - 606 problems recorded
    - » 59 a/c-to-a/c conflicts
    - » 547 a/c-to-SUA conflicts
- Modified trajectories with agent models activated
  - 644 potential problems
  - Over 96% of problems resolved by agents
- Negotiation was required for over 8% of successfully resolved aircraft-to-aircraft conflicts



Summary of Study #2

- Developed an agent-based simulation toolkit for the study of advanced ATM operations in a distributed control environment
  - Modeled key human decision-makers in ATM environment: pilot, air traffic controller, airline dispatcher
  - Developed a framework for distributed decision-making, based on the protocol of Principled Negotiation
  - Integrated human behavior representations within a simulated air traffic environment (FACET) for demonstration and analysis

- Conducted a numerical experiment to assess the need for distributed decision-making in realistic air traffic scenarios
  - Results indicate that distributed decision-making can solve complex ATM problems, and was required for more than 8% of aircraft-to-aircraft conflicts in the simulated ZLA scenario

Study #3

Properties of Air Traffic Conflicts for Free and Structured Routing

Karl Bilimoria and Hilda Lee

Paper No. 2001-4051
AIAA Guidance, Navigation, and Control Conference
Montréal, CANADA
August 2001

Problem Definition

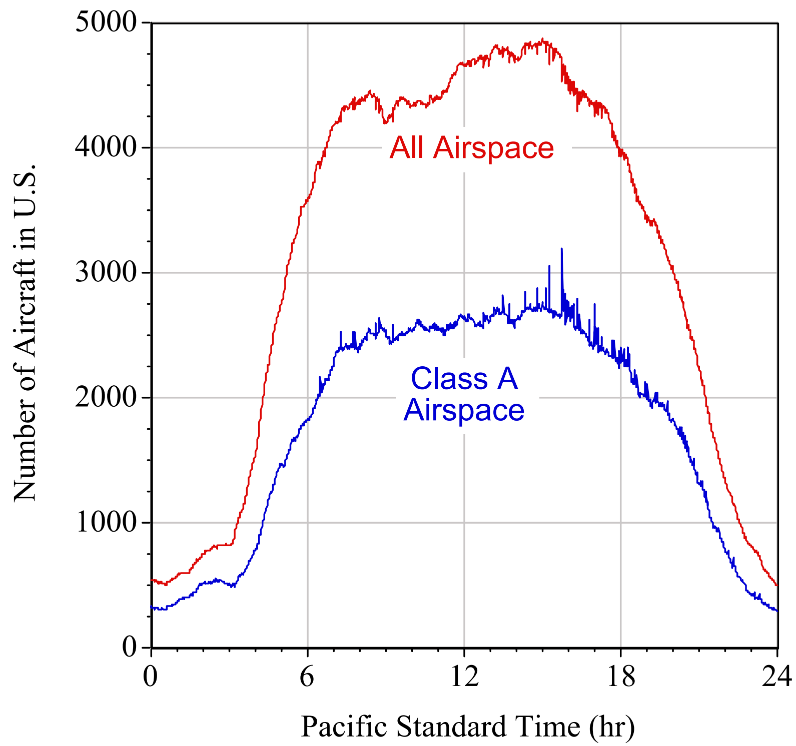
- Research Questions:
  - How often would conflicts occur in the absence of corrective action?
  - What are the key properties of conflicts?
  - What is the level of interaction between individual conflicts?
  - Does free routing significantly change the number/nature of conflicts?

- Approach
  - Conduct simulation based on real traffic data from current operations
    - Aircraft-to-aircraft conflicts only
    - Wind effects not modeled
  - Study conflicts only in Class A airspace (at or above FL180)
    - Trajectories in lower airspace can vary significantly from flight plans
    - Significant percentage of flights in lower airspace are VFR flights

Conflict Data Collection

- Enhanced Traffic Management System (ETMS) data for a 24-hr period in March 2001
  - 57,402 aircraft total
  - 37,926 aircraft in Class A airspace

Aircraft Count vs. Time

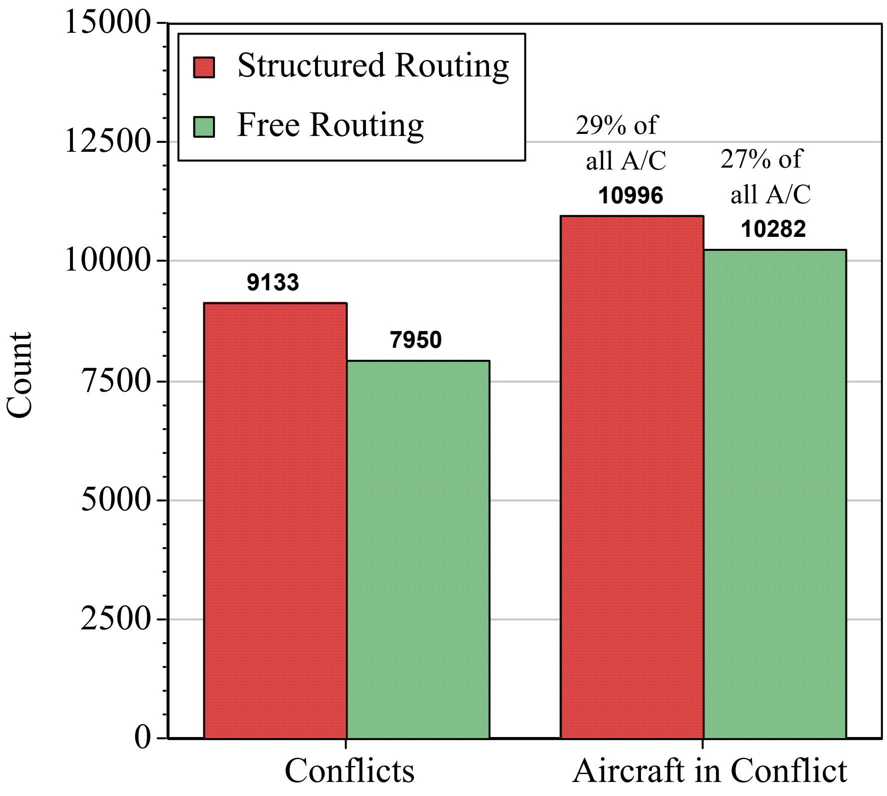


- Birth points and times captured from ETMS data

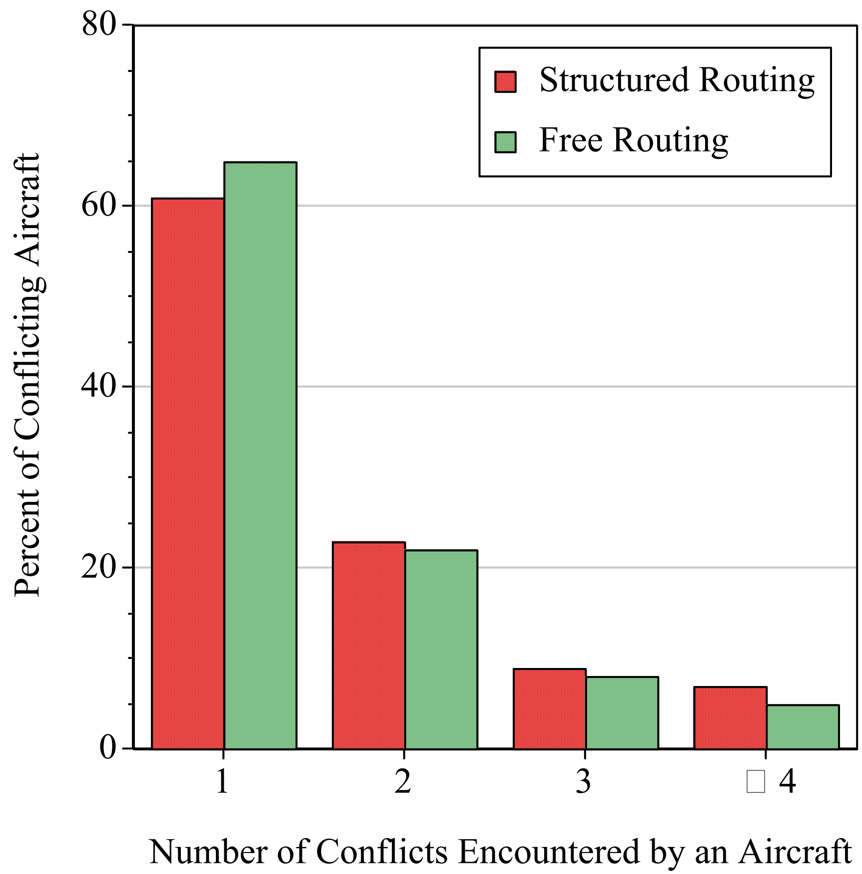
- Aircraft fly to destination in 3-D simulation, with Conflict Resolution **OFF**
  - Free (great circle) routing
  - Structured (flight plan) routing

Results: Number of Conflicts

Counts of Conflicts and Aircraft

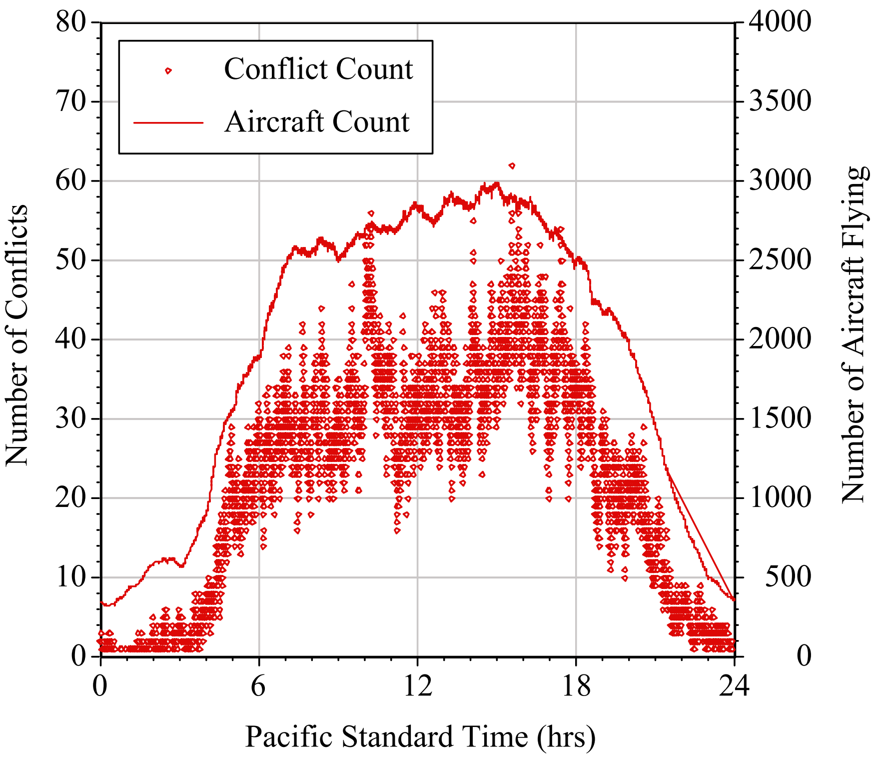


Number of Conflicts per Aircraft

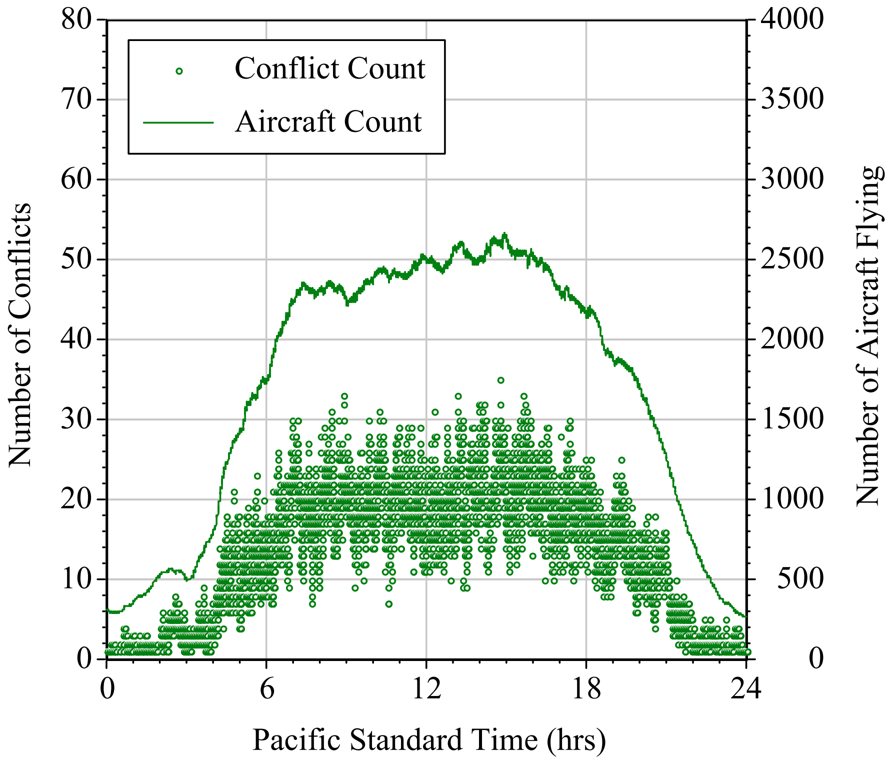


Results: Conflict Counts vs. Time

Structured Routing

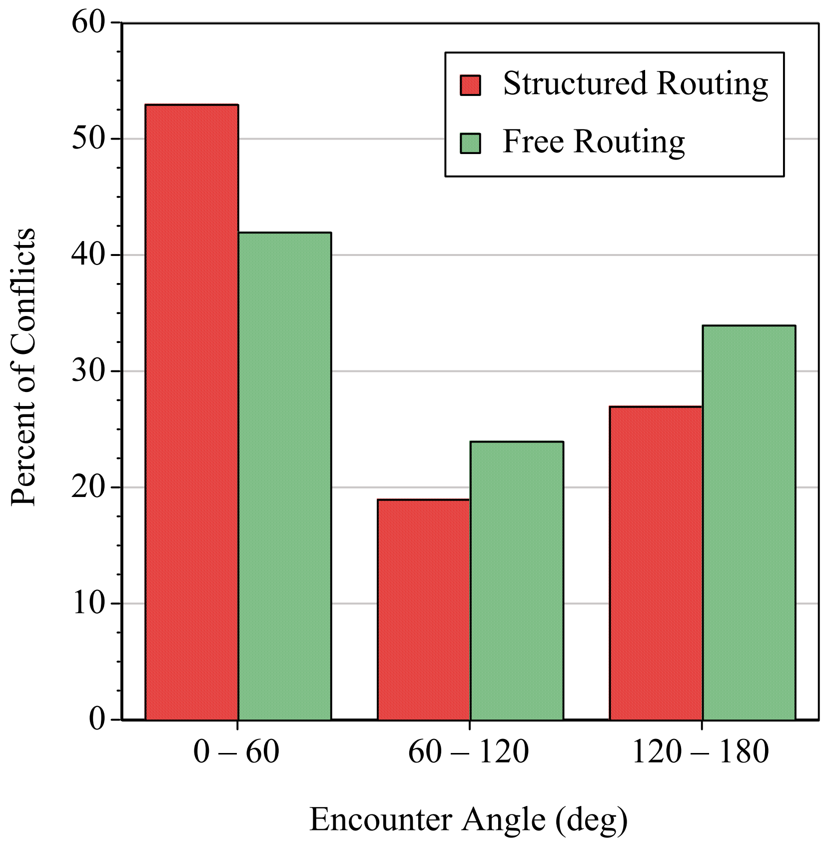


Free Routing

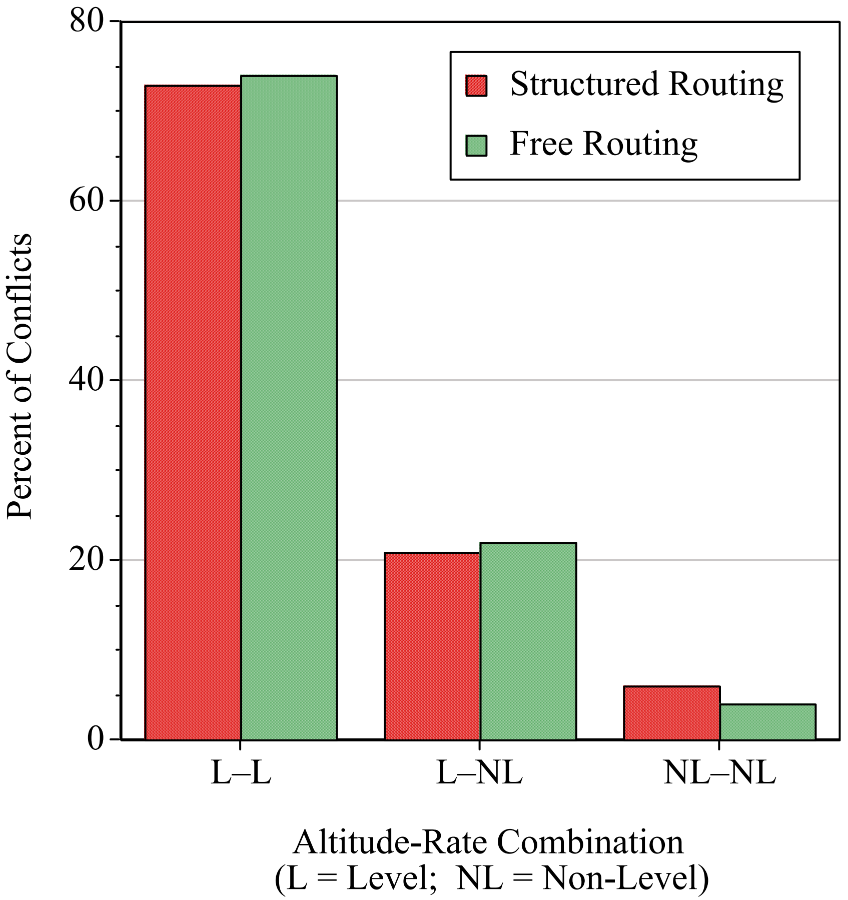


Results: Conflict Properties

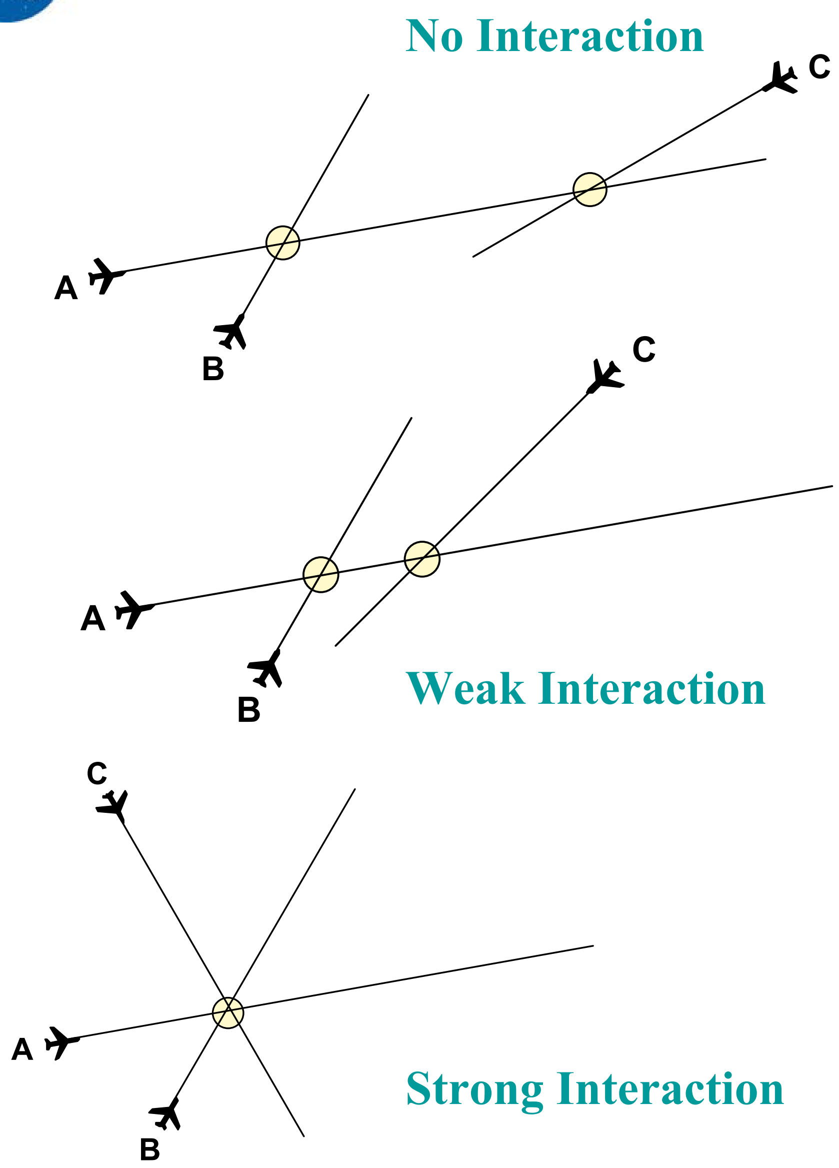
Encounter Angle Distributions

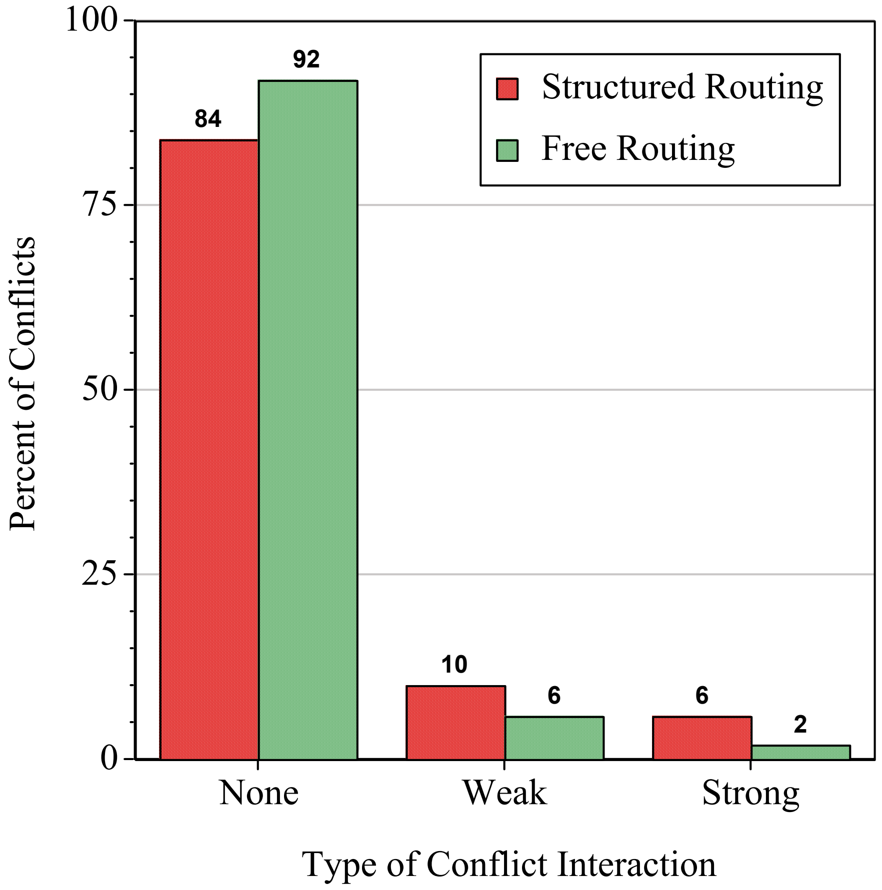


Altitude-Rate Distributions



Results: Conflict Interactions





Summary of Study #3

- Investigated conflict properties for free and structured routing in a simulation based on 24 hours of real traffic data (ETMS)
  - Results for conflicts in Class A airspace
- Less than 30% of aircraft ever experienced a conflict
  - Of these, about 40% experienced more than one conflict
- Most (~85%) conflicts had no significant interaction
  - Useful information for design of conflict resolution tools
- Free routing has ~10% fewer conflicts than structured routing
  - Supports feasibility of Free Flight concept

Concluding Remarks

- Conducted fast-time simulation experiments to evaluate feasibility of airborne self-separation for Free Maneuvering

- Key results
  - Conflicts can be resolved without central coordination
  - Negotiated resolution can solve highly constrained conflicts
  - Free routing reduces the number and complexity of en route conflicts for current traffic pattern (schedule, origin-destination pairs, etc.)

- All results support feasibility of airborne separation assurance for Free Maneuvering under DAG-TM operations
  - Work presented here is only a small part of the overall effort
  - More studies necessary for final concept validation

Related Work on Separation Assurance

1. Bilimoria, K.D. and Lee, H.Q., "Aircraft Conflict Resolution with an Arrival Time Constraint," Paper No. 2002-4444, *AIAA Guidance, Navigation, and Control Conference,* August 2002.
2. Mueller, K.T., Schleicher, D., and Bilimoria, K.D, "Conflict Detection and Resolution with Traffic Flow Constraints," Paper No. 2002-4445, *AIAA Guidance, Navigation, and Control Conference,* August 2002.
3. Dugail, D., Feron, E., and Bilimoria, K.D, "Conflict-Free Conformance to En Route Flow-Rate Constraints," Paper No. 2002-5013, *AIAA Guidance, Navigation, and Control Conference,* August 2002.
4. Dugail, D., Feron, E., and Bilimoria, K., "Stability of Intersecting Aircraft Flows using Heading Change Maneuvers for Conflict Avoidance," Paper INV-5005, *American Control Conference,* May 2002.
5. Krozel, J., Peters, M., Bilimoria, K.D., Lee, C., and Mitchell, J.S.B., "System Performance Characteristics of Centralized and Decentralized Air Traffic Separation Strategies," *4th USA/Europe Air Traffic Management Research and Development Seminar*, December 2001; also, *Air Traffic Control Quarterly*, Vol. 9, No. 4, December 2001, pp. 311–332.
6. Mao, Z.-H., Feron, E., and Bilimoria, K., "Stability and Performance of Intersecting Aircraft Flows under Decentralized Conflict Avoidance Rules," *IEEE Transactions on Intelligent Transportation Systems*, Vol. 2, No. 2, June 2001, pp. 101–109.
7. Bilimoria, K.D., "Methodology for the Performance Evaluation of a Conflict Probe," *Journal of Guidance, Control, and Dynamics*, Vol. 24, No. 3, May-June 2001, pp. 444–451.
8. Bilimoria, K.D., "A Geometric Optimization Approach to Aircraft Conflict Resolution," Paper No. 2000-4265, *AIAA Guidance, Navigation, and Control Conference,* August 2000.

Papers available upon request

Discussion