Simulation of Air Traffic Controller and Automation Performance

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NASA Aviation Safety Program System-Wide Accident Prevention Project
NASA Vehicle Systems Program Quiet Aircraft Technology Project
NASA Airspace Systems Program Advanced Air Transportation Technology Project

Overview

- Introduction
- En route controller agents
- TRACON automation and controller agents
- Future research
- Conclusion

Introduction

- Why simulate air traffic controller and automation performance?

Complement Traditional Design Techniques

Ames Research Center — Information Sciences & Technology

- Complex human-machine system design

1. Formulate concepts
2. Construct prototypes
3. Conduct large-scale simulations, part-task studies
4. Conduct field studies

- Expensive, time-consuming, iterative

Airspace Operations Laboratory (AOL)

Not shown:
Flight Deck Display Research Laboratories

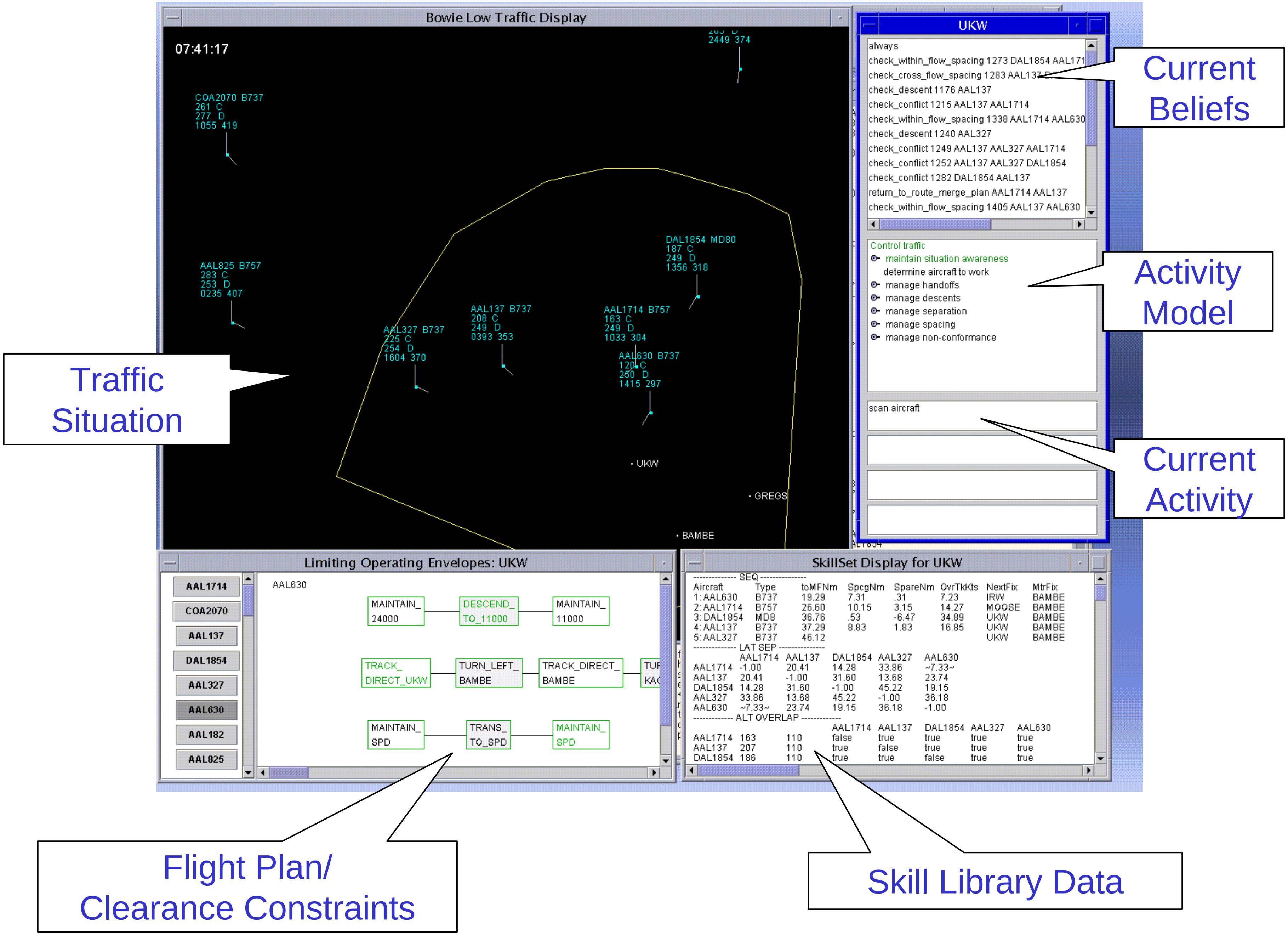
- Simulations promise inexpensive means of understanding concept safety/risks to complement human-in-the-loop research

ATC Tool Design

- Mismatched air and ground automation
  - Aircraft Flight Management Systems (FMSs) enable precise 4D flight
  - Air traffic controllers lack tools
  - Instead use inefficient tactical methods or introduce large ‘spacing buffers’

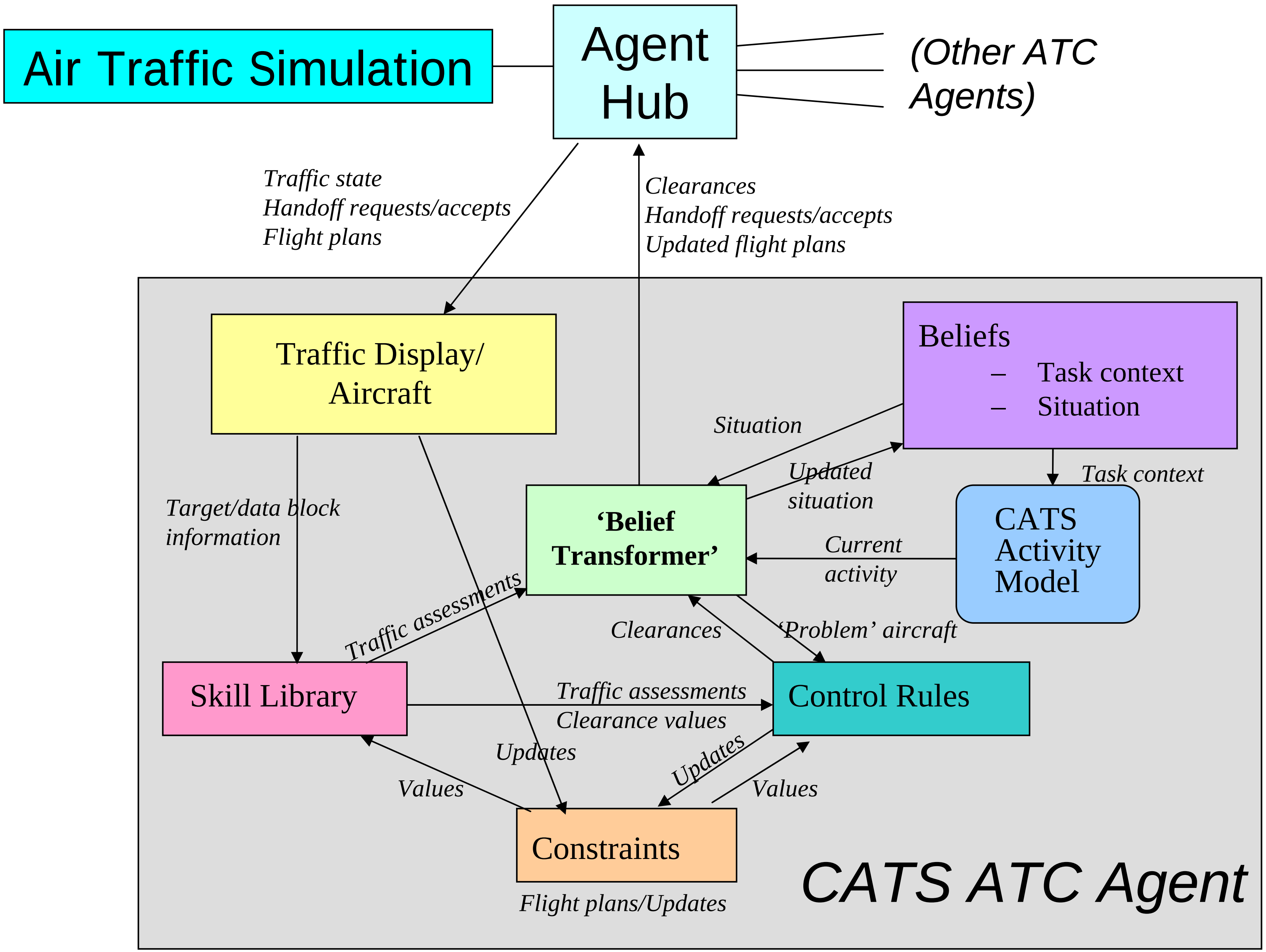
Potential Contributions

- Practitioner roles and responsibilities
- Controller strategy and tool interactions
- Airspace and traffic effects
- Potential errors and error effects
- Effects of other constraints
- Robustness mechanisms
- Safety/risk assessment
- Scenario identification, training requirements, and performance baselines for human-in-the-loop studies



Bowie Low Traffic Display
07:41:17
COA2070 B737
AAL825 B757
AAL327 B737
AAL137 B737
AAL1714 B757
DAL1854 MD80
AAL630 B737
UKW
GREGS
BAMBE
UKW
always
check_within_flow_spacing 1273 DAL1854 AAL171
check_cross_flow_spacing 1283 AAL137
check_descent 1176 AAL137
check_conflict 1215 AAL137 AAL1714
check_within_flow_spacing 1338 AAL1714 AAL630
check_descent 1240 AAL327
check_conflict 1249 AAL137 AAL327 AAL1714
check_conflict 1252 AAL137 AAL327 DAL1854
check_conflict 1282 DAL1854 AAL137
return_to_route_merge_plan AAL1714 AAL137
check_within_flow_spacing 1405 AAL137 AAL630
Control traffic
maintain situation awareness
determine aircraft to work
manage handoffs
manage descents
manage separation
manage spacing
manage non-conformance
scan aircraft
Limiting Operating Envelopes: UKW
AAL1714
COA2070
AAL137
DAL1854
AAL327
AAL630
AAL182
AAL825
AAL630
MAINTAIN_ 24000
DESCEND_ TO_11000
MAINTAIN_ 11000
TRACK_ DIRECT_UKW
TURN_LEFT_ BAMBE
TRACK_DIRECT_ BAMBE
MAINTAIN_ SPD
TRANS_ TO_SPD
MAINTAIN_ SPD
SkillSet Display for UKW
SEQ
Aircraft Type toMFNm SpcgNm SpareNm OvrTkKts NextFix MtrFix
1: AAL630 B737 19.29 7.31 .31 7.23 IRW BAMBE
2: AAL1714 B757 26.60 10.15 3.15 14.27 MOOSE BAMBE
3: DAL1854 MD8 36.76 .53 -6.47 34.89 UKW BAMBE
4: AAL137 B737 37.29 8.83 1.83 16.85 UKW BAMBE
5: AAL327 B737 46.12 UKW BAMBE
LAT SEP
AAL1714 AAL137 DAL1854 AAL327 AAL630
AAL1714 -1.00 20.41 14.28 33.86 ~7.33~
AAL137 20.41 -1.00 31.60 13.68 23.74
DAL1854 14.28 31.60 -1.00 45.22 19.15
AAL327 33.86 13.68 45.22 -1.00 36.18
AAL630 ~7.33~ 23.74 19.15 36.18 -1.00
ALT OVERLAP
AAL1714 AAL137 DAL1854 AAL327 AAL630
AAL1714 163 110 false true true true true
AAL137 207 110 true false true true true
DAL1854 186 110 true true false true true
Current Beliefs
Activity Model
Traffic Situation
Current Activity
Flight Plan/ Clearance Constraints
Skill Library Data

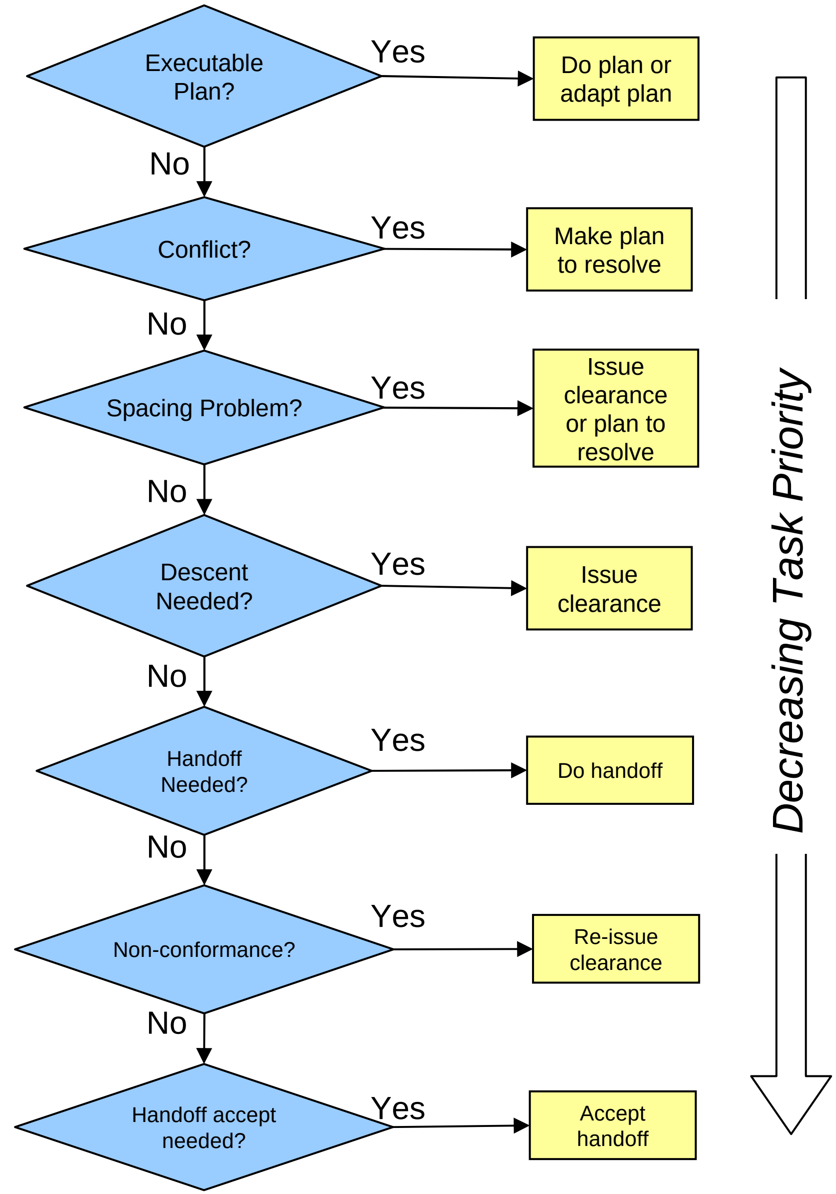
Augmented Multi-Agent Architecture



Activity Model and ‘Control Flow’

Activity Model

- Maintain situation awareness
  - Monitor traffic display
  - Scan aircraft
- Determine aircraft to work
- Manage handoffs
  - Accept aircraft
    - Accept handoff
    - Roger check-in
  - Initiate handoff
    - Inform other controller
    - Issue frequency change
- Manage descents
  - Issue descent clearance
- Manage separation
  - Evaluate separation clearance options
  - Issue separation clearance
- Manage spacing
  - Evaluate spacing clearance options
  - Issue spacing clearance
- Manage nonconformance
  - Re-issue clearance



CATS ATC Agent Beliefs

Task context – 'context specifiers'

Always
Display needs scanning
Looked at traffic display
Have aircraft to work
Know which aircraft to accept
Know which aircraft to hand off
Know which aircraft to descend
Factors identified (refers to conflict aircraft)
Spacing aircraft identified
Know which aircraft to clear (separate)
Know which aircraft to space
Know which aircraft is not conforming

'Situation' context –
• *beliefs about current situation* • *memory for 'problem status'*
• *prospective memory for plans*

Check_cross_flow_spacing [time] [aircraft]
Check_within_flow_spacing [time] [aircraft]
Check_conflict [time] [aircraft]
Check_descent [time] [aircraft]
Cross_flow_spacing [aircraft clusters]
Within_flow_spacing [aircraft clusters]
Conflicts [aircraft clusters]
Sector_aircraft [aircraft]
Plan_exec [aircraft]

Spacing Control Rules

- for achieving required in-trail spacing within flows, and across flows that merge

- If excess spacing, **speed up/plan to match speeds**

Requires planning

- If insufficient spacing:
  - If no aircraft in front of *front* or behind *back*, **stagger speeds**
  - If no aircraft in front of *front*, but aircraft behind *back*, **speed lead aircraft up**
  - If aircraft in front of *front*, but not behind *back*, **slow back aircraft**
  - If aircraft in front of *front*, and behind *back*, require vectors (handle as conflict using separation control rules)

'*front*' and '*back*' refer to aircraft in roles bound to current aircraft

Separation Control Rules

- for resolving conflicts and effecting merges

If *front* directly in front and no aircraft behind *back*:

- If merge, **plan to merge**
- Otherwise, **plan minimal offset**

If *front* directly in front and aircraft behind *back*:

- If merge, **plan to merge**
- Otherwise, **plan minimal offset** and **plan to match vectors** for aircraft behind *back*

If *front* in front sequentially and no aircraft behind *back*:

- If merge, **plan to turn in to merge**
- Otherwise, **plan to vector and turn back**

If *front* in front sequentially and aircraft behind *back*:

- If merge, **plan to turn in to merge**
- Otherwise, **plan to vector and turn back** and **plan to match vectors** for aircraft behind *back*

- Multiple aircraft conflicts
  - Only handle in cases of merge, using **plan to merge** or **plan to turn in to merge**

All require planning

Plan ‘Steps’ That Comprise Control Plans

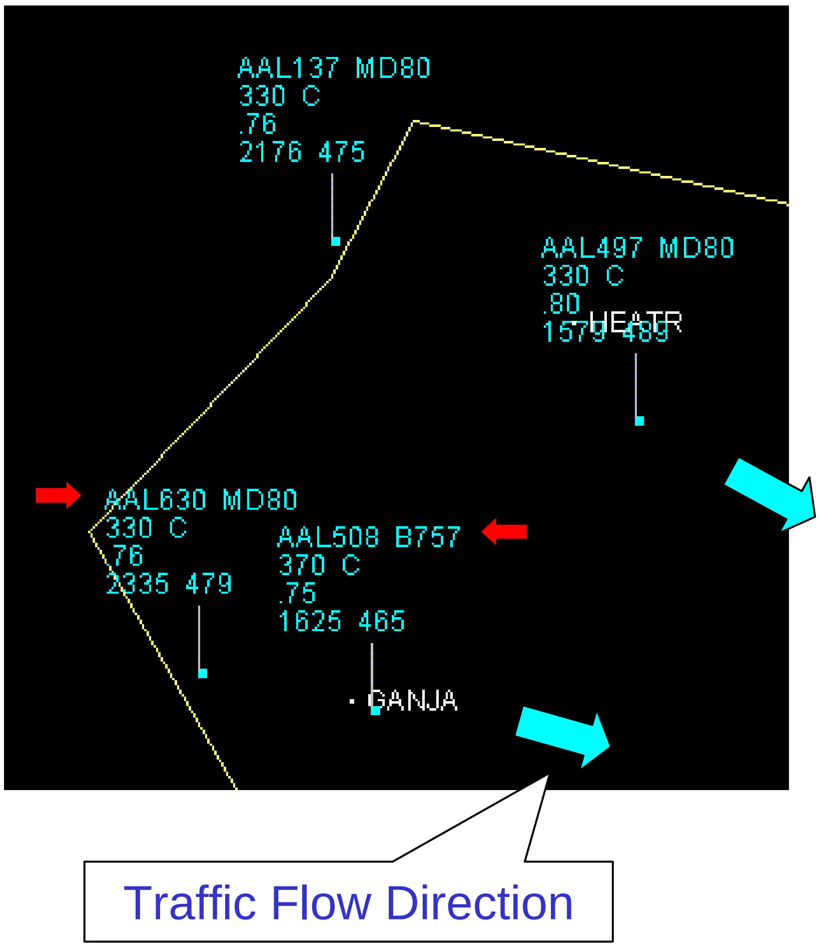
- Lateral dimension:
  - Delay vector
  - Match planned lead delay vector
  - Turn back vector
  - Match planned lead turn back vector
  - Return to heading
  - Return to route
  - Direct-to
  - Meter fix direct-to
  - Return to route-merge
- Vertical dimension:
  - Climb temporary altitude
  - Descend temporary altitude
- Speed dimension:
  - Match lead speed
  - Match lead mach
  - Accelerate
  - Accelerate-mach
  - Decelerate
  - Decelerate-mach
  - Allow to pass

- each plan step contains execution conditions and roles (e.g., ‘front’*) bound to plan at formulation time*

Plan Adaptation and Execution Conditions

- **Delay vector**
  - If handed off, send direct to next waypoint
  - If close to Meter Fix, send direct to meter fix
  - If planned time, execute as is
- **Match planned lead delay vector**
  - If handed off, send direct to next waypoint
  - If close to Meter Fix, send direct to meter fix
  - If back aircraft null, execute as is
  - If back aircraft doesn't have a plan to turn out, execute as is
  - If planned time, execute as is
- **Turn back vector**
  - If handed off, send direct to next waypoint
  - If close to Meter Fix, send direct to meter fix
  - If planned time, execute as is
  - If not excess spacing or insufficient spacing, abandon
- **Match planned lead turn back vector**
  - If handed off, send direct to next waypoint
  - If close to Meter Fix, send direct to meter fix
  - If front aircraft null, execute as is
  - If front aircraft doesn't have a plan to turn back, execute as is
  - If planned time, execute as is
  - If not excess spacing or insufficient spacing, abandon
- **Return to heading**
  - If handed off, send direct to next waypoint
  - If close to sector bounds, execute as is
  - If close to Meter Fix, send direct to meter fix
  - If not excess spacing or insufficient spacing, abandon
- **Return to route**
  - If handed off, send direct to next waypoint
  - If close to sector bounds, execute as is
  - If aircraft has passed the next fix, send direct to the following fix
  - If close to Meter Fix, send direct to meter fix
  - If not excess spacing or insufficient spacing, abandon
- **Direct-to**
  - (not used- superceded by return to route)
- **Meter fix direct-to**
  - (not used- superceded by return to route)
- **Return to route-merge**
  - If handed off, send direct to next waypoint
  - If front aircraft has passed the next fix, execute as is
  - If aircraft has missed it's slot, re-plan to merge
  - If have required merge spacing and aircraft has been on a vector for at least 60 secs, execute as is

Example Spacing Operations



1. Identify ‘sector aircraft’ AAL630, AAL508, and AAL497

2. Identify ‘within-flow spacing’ problem for AAL630 and AAL508

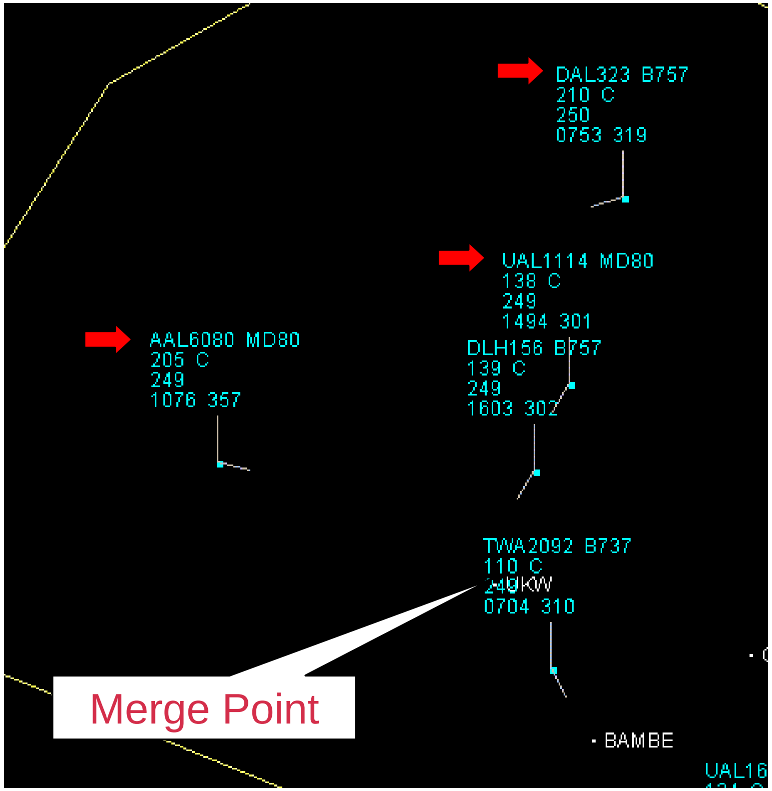
3. Bind AAL630 to role ‘back’ in AAL508; bind AAL508 to ‘front’ in AAL630

4. No higher priority problems, so access control rules; arrive at strategy ‘speed up/plan to match speeds’

5. Accelerate AAL630

6. When proper spacing achieved, execute ‘match lead mach’ plan by issuing clearance for AAL630 to match speed of AAL508

Example Separation (Merge) Operations



1. Identified AAL6080 in conflict with UAL1114, UAL1114 in front sequentially, no aircraft behind AAL6080

2. Identified merge at UKW, executed ‘plan to turn in to merge’ strategy: AAL6080 to heading 095, plan for ‘return to route - merge’

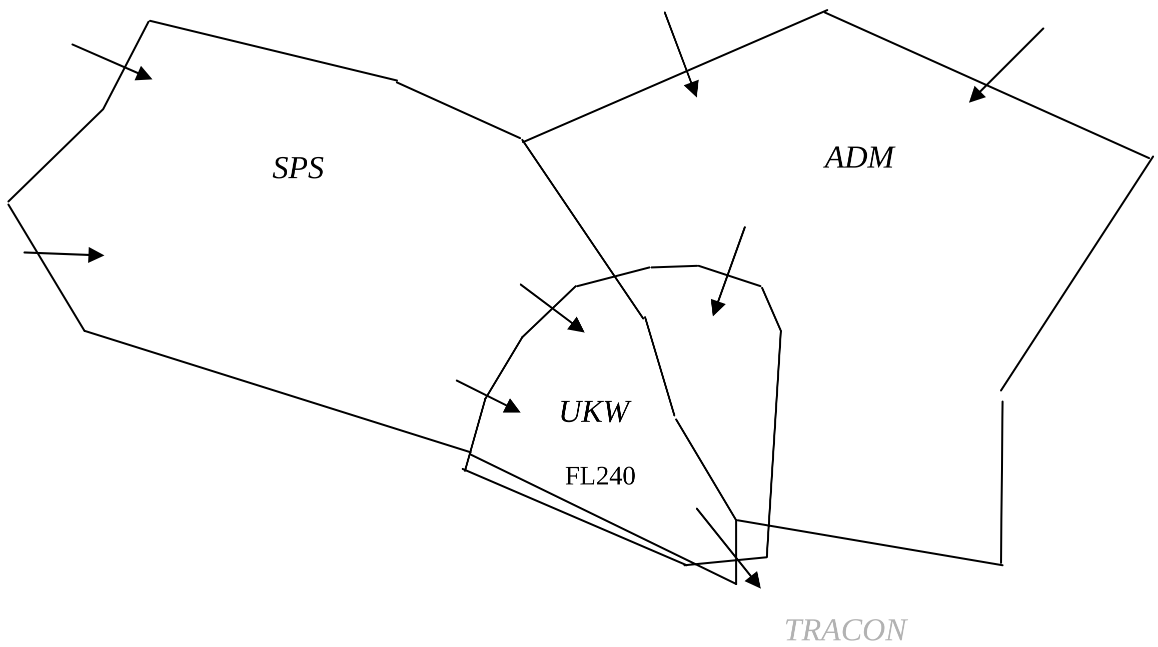
3. Also, DAL323 in conflict with AAL6080: DAL323 to heading 245, plan for ‘return to route - merge’

4. NOW, repeatedly assess AAL6080’s distance to merge point versus UAL1114’s, and DAL323’s versus AAL6080’s

5. Eventually find required spacing between UAL1114 and AAL6080, execute AAL6080’s ‘return to route - merge’ plan: AAL680 direct to UKW; finally, DAL323 direct to UKW to complete merge

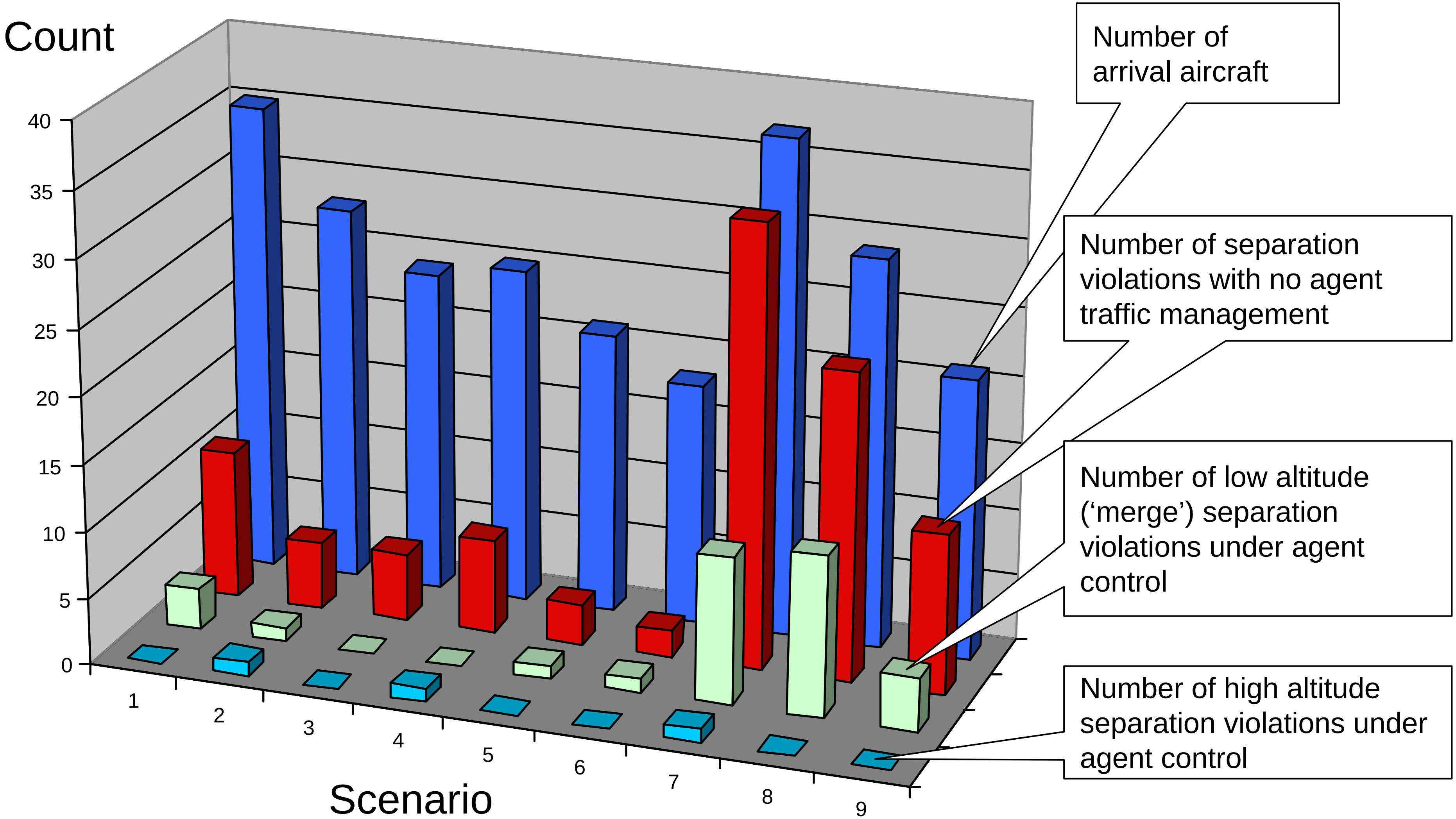
Test Environment

- Airspace:



- Distributed Air/Ground arrival traffic scenarios

Performance Assessment



Error-Generation for Safety Assessment

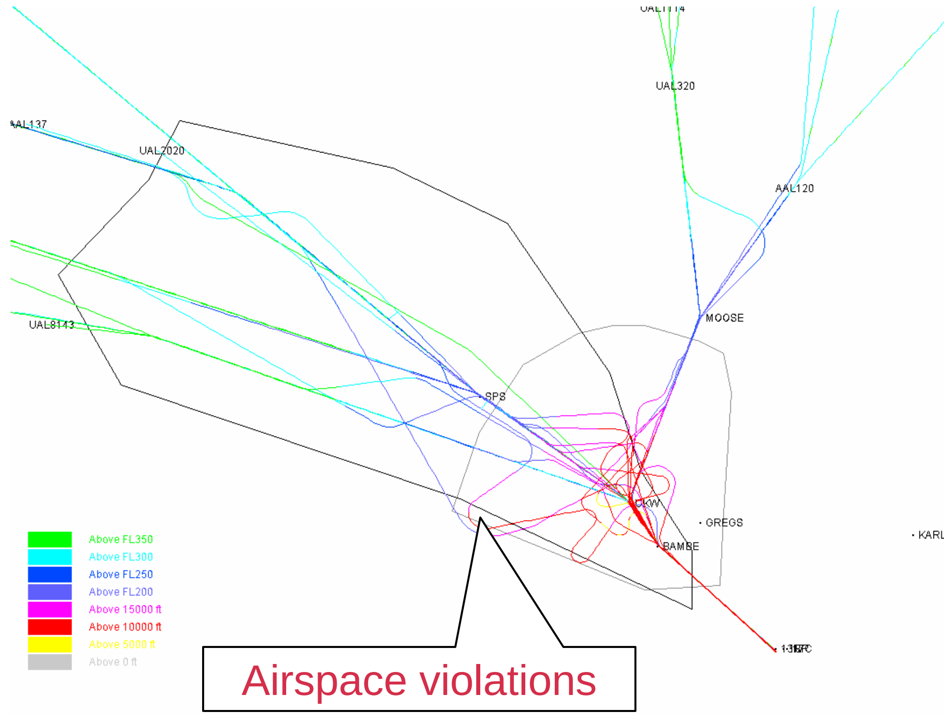
Probabilistic Error Mechanisms for Monte Carlo-style Safety Analyses:

1. ‘Forget’ a belief, or confuse aircraft in belief for another aircraft

2. Confuse ‘front’ and ‘back’ aircraft during control rule application

3. ‘Misread’ displayed information, or ‘incorrectly recall’ information

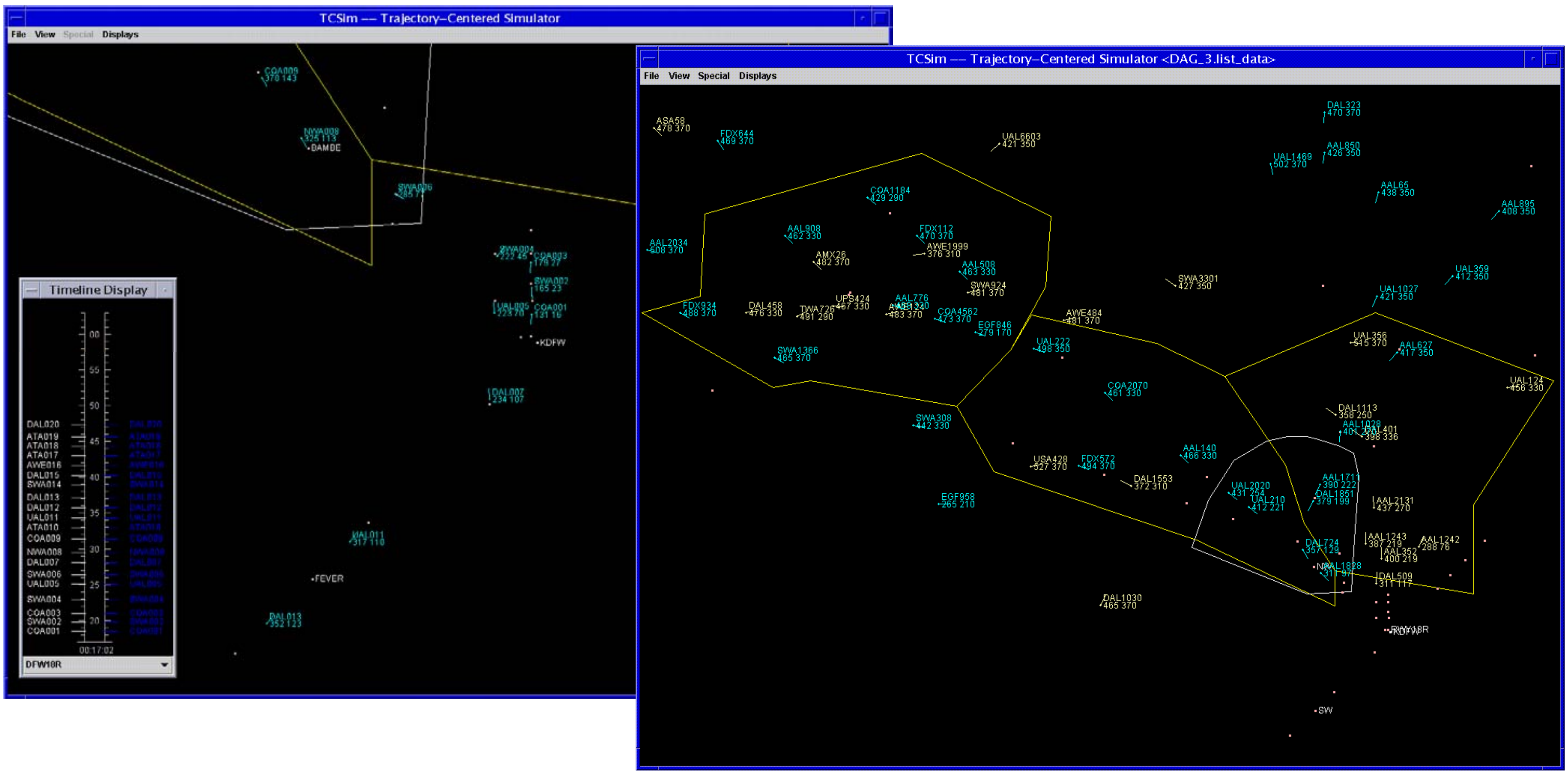
4. Confuse clearance type or contents when issuing a clearance



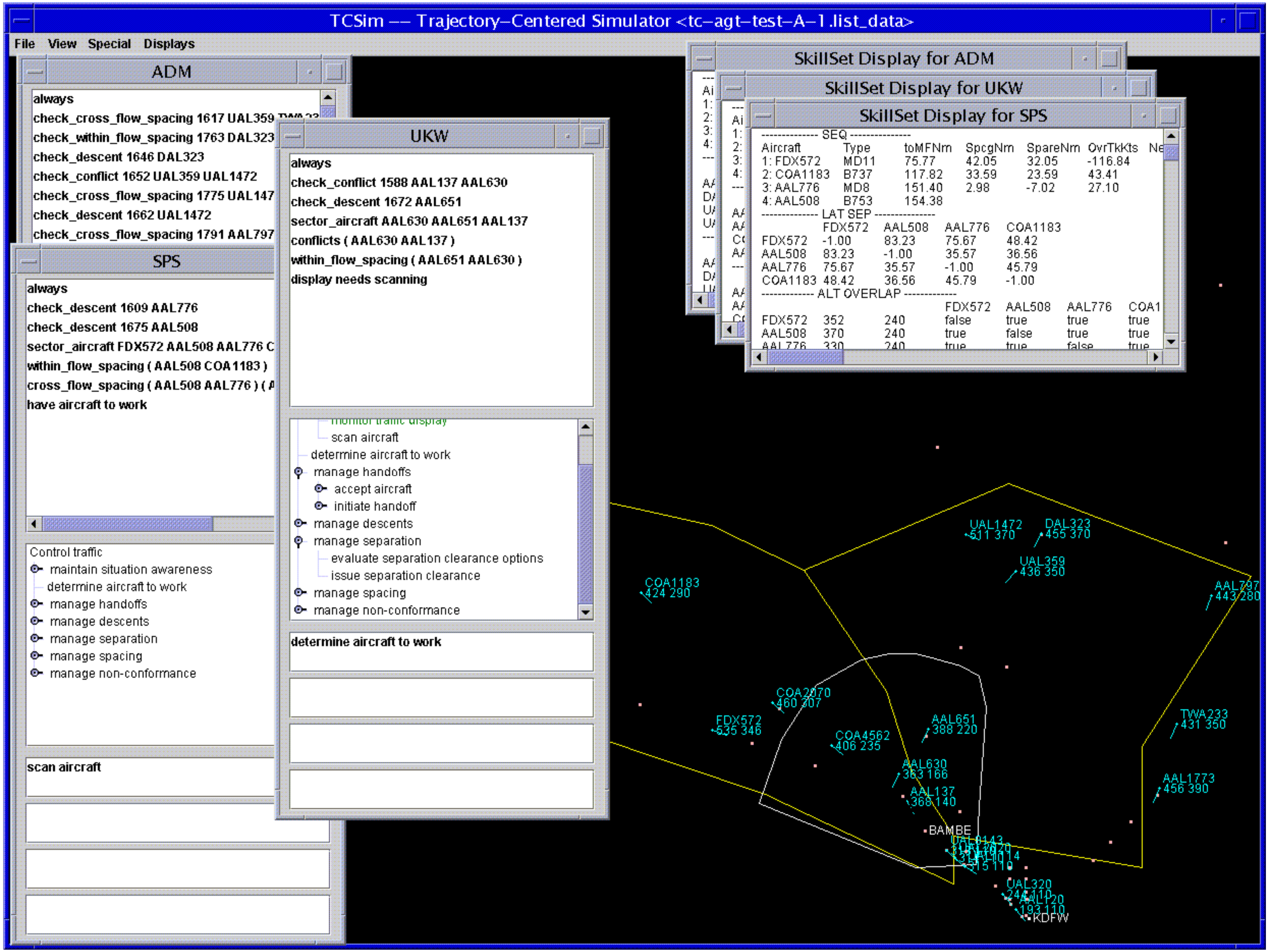
Interesting results:

- Error-chaining effects
- Inherent error-tolerance of agents

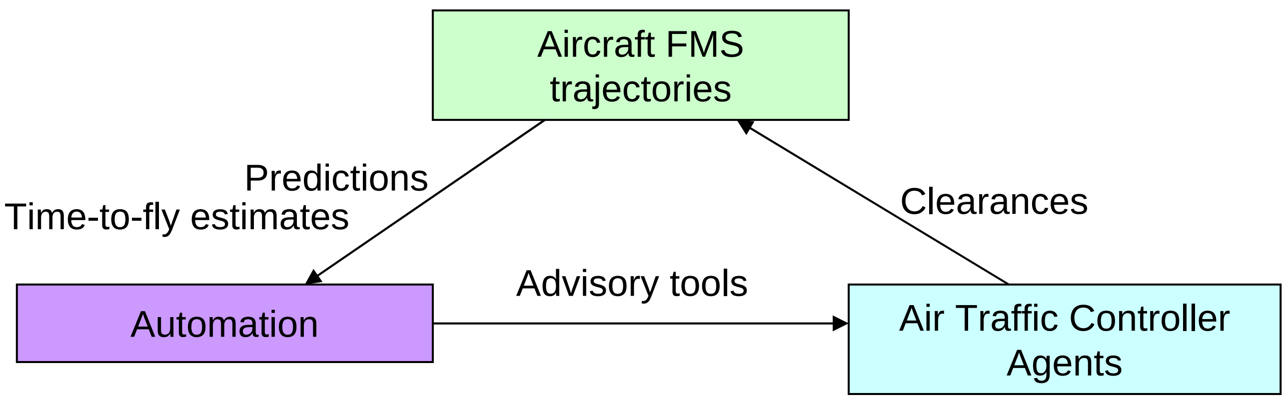
Trajectory-Centered Simulator (TCSim) Fast-Time Simulations

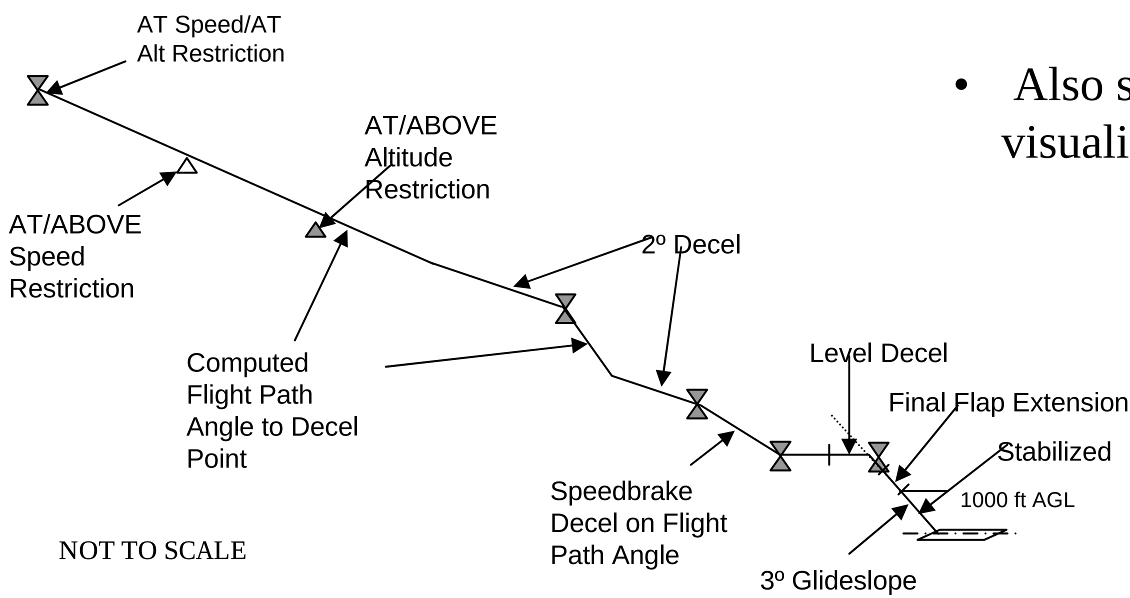


CATS ATC Agent Integration



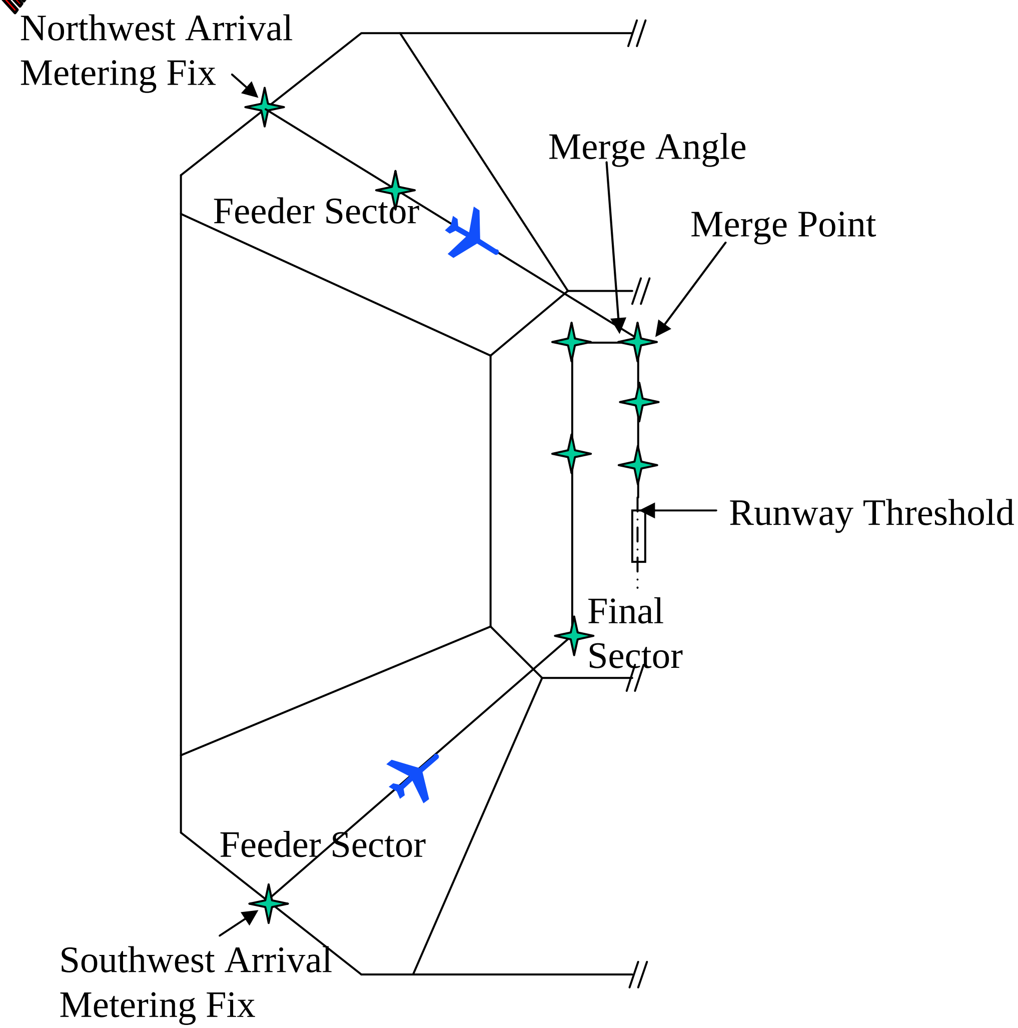
TCSim Concept





- Also supports scenario visualization & generation

TRACON Control Problem



- TRACON operations
  - Limited ability to control traffic without inefficiencies/ flow disruptions
- 'Continuous Descent Approach'
  - Provides fuel/noise benefits
  - Throughput limited by poor predictability
- LNAV/VNAV trajectory-based operations
  - Predictability with suitable tools
  - En route concept compatibility
    - Aircraft adhere to metering schedule

Analysis Methodology

- Establish baseline traffic flow metrics
  - Remove variability, examine route-related factors
- Examine disturbance effects
  - Perform Monte Carlo simulations with prediction and flight execution errors

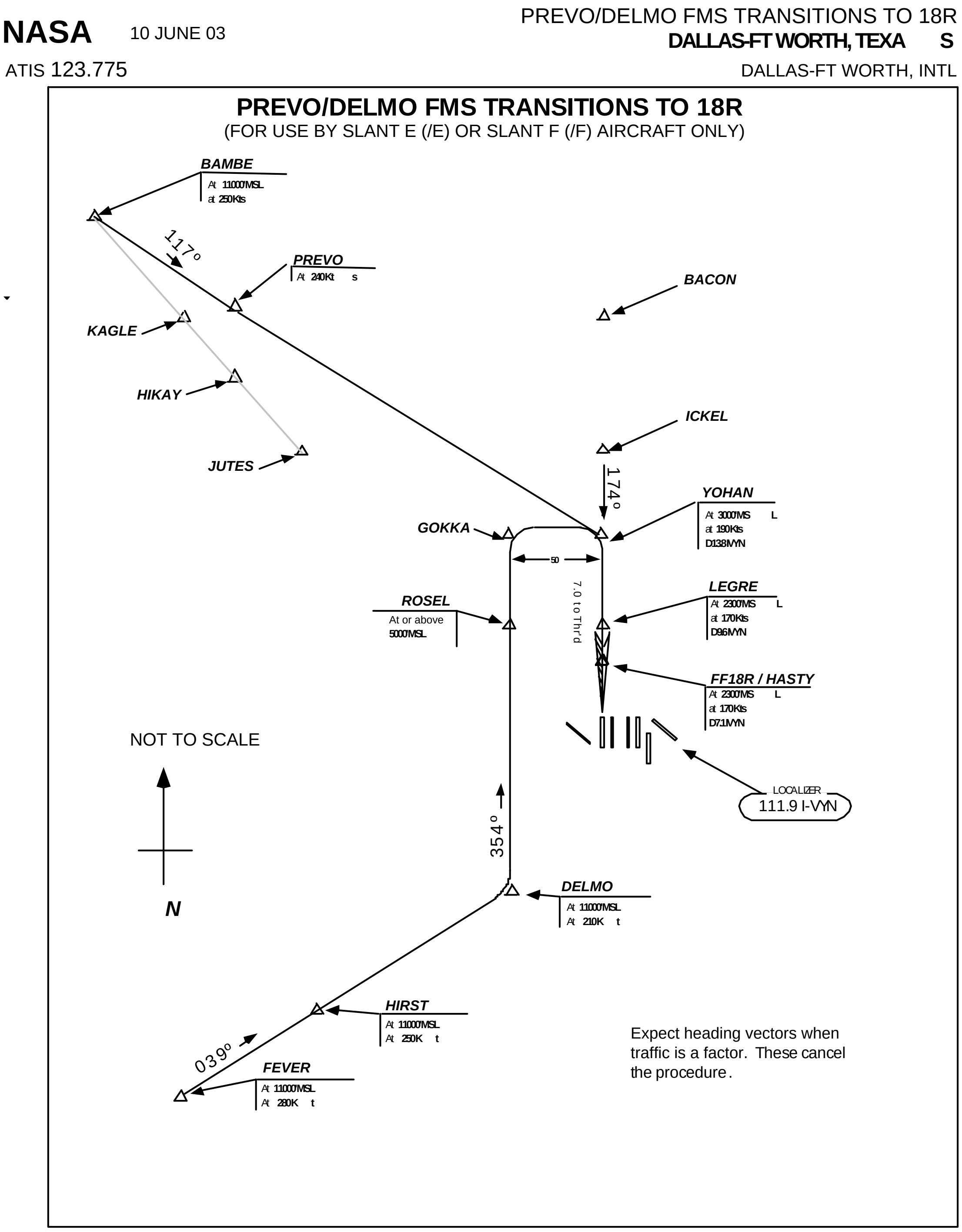
Domain focus

Strategy focus

- Assess control authority
  - Assess control possible with particular clearances in specific domain
- Analyze performance with air traffic controller agents
  - Exercise control strategies in Monte Carlo simulations, compare metrics with domain analyses

Candidate TRACON ATM Concepts

- Assume coordinated meter fix schedules that account for TRACON flight time and runway wake vortex spacing
- How well can TRACON speed adjustments compensate for schedule deviations?
  - Working hypothesis: Automatically generated speed advisories can reduce required spacing buffer to acceptably small values
- Variations:
  - ‘Control points,’ predicted ETA locations, cancel one or more restrictions?



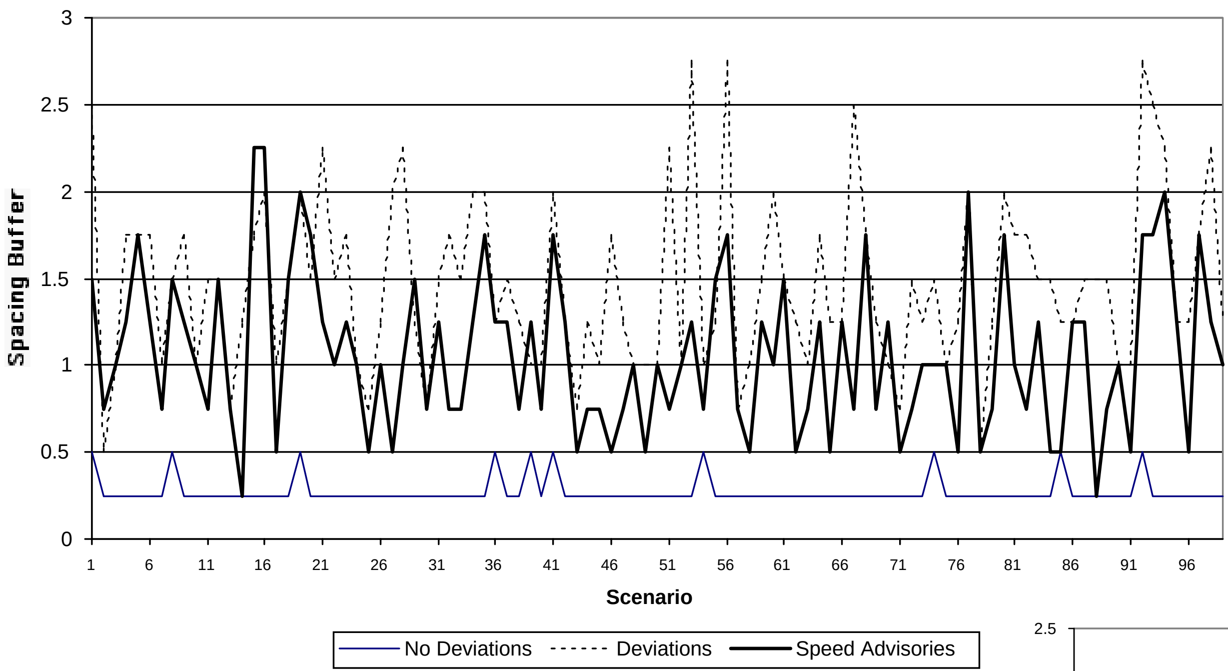
Test Scenarios

- Charted approach transitions
- Traffic
  - Twenty aircraft
  - Two Heavy's, Four 757's, Fourteen Large's
  - At least five from Northwest, Southwest
- Scheduling
  - No compensation for final approach compression effects
- Disturbances
  - MF crossing - N(0, 15)
  - Landing speed - N(0, 5)
  - Predicted winds
  - Flight technical errors

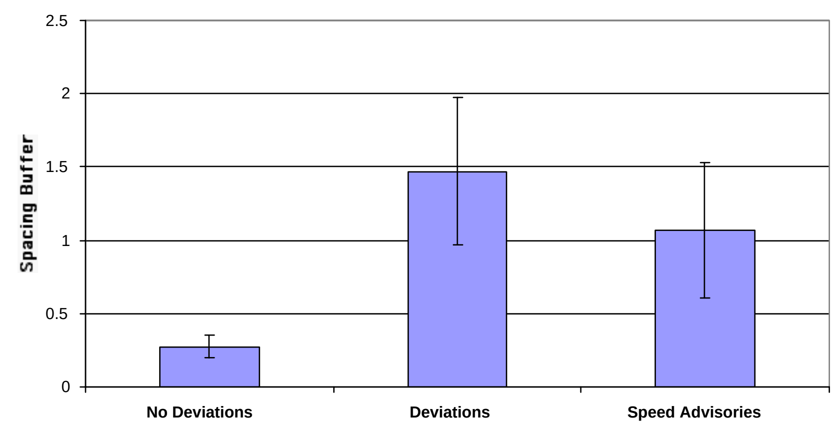
Test Scheme

- Metric
  - Additional spacing buffer required to eliminate separation violations
- Process
  - Generate scenario
  - Schedule aircraft with proper wake vortex spacing
  - Increment ‘additional spacing buffer’ .25 nm, *repeat* until no separation violations
  - Introduce disturbances, *repeat*
  - Introduce air traffic controller agents issuing speed advisories (slow-downs ONLY) to null runway ETA-RTA differences, *repeat*

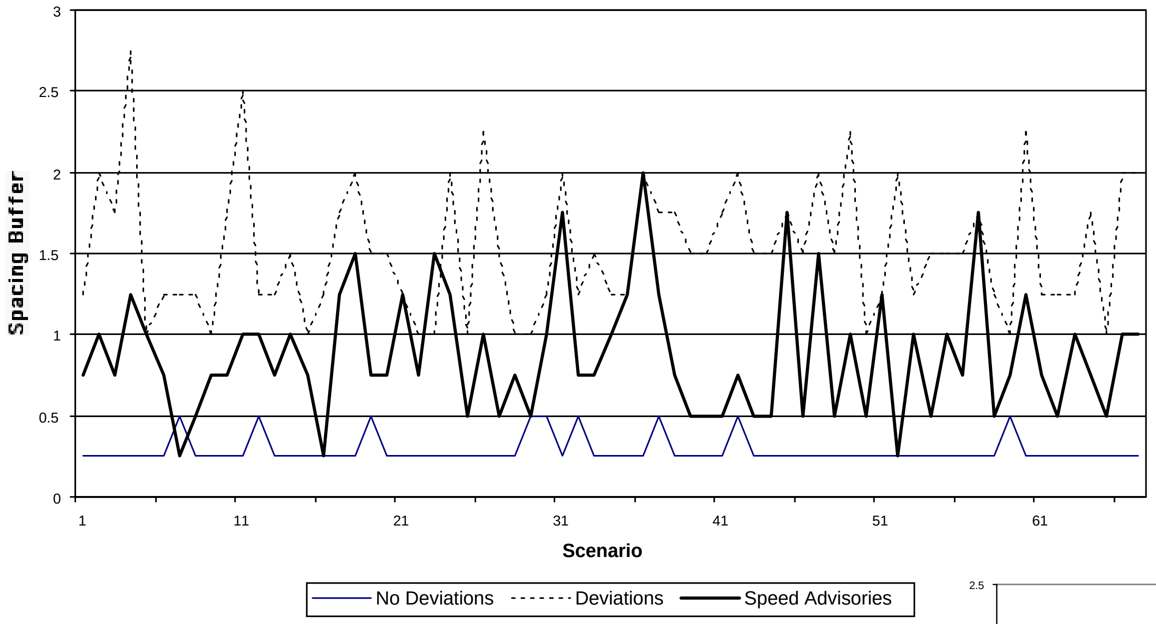
Results

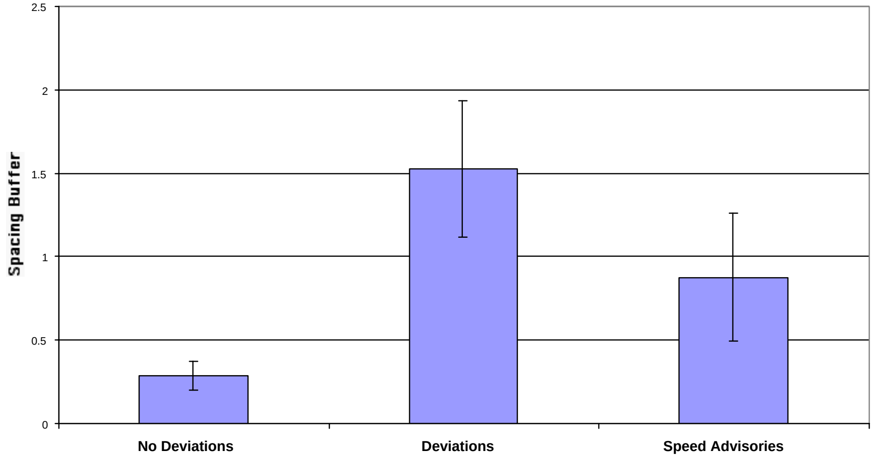


- Speed advisories help reduce required spacing buffer, but don’t eliminate effects of deviations



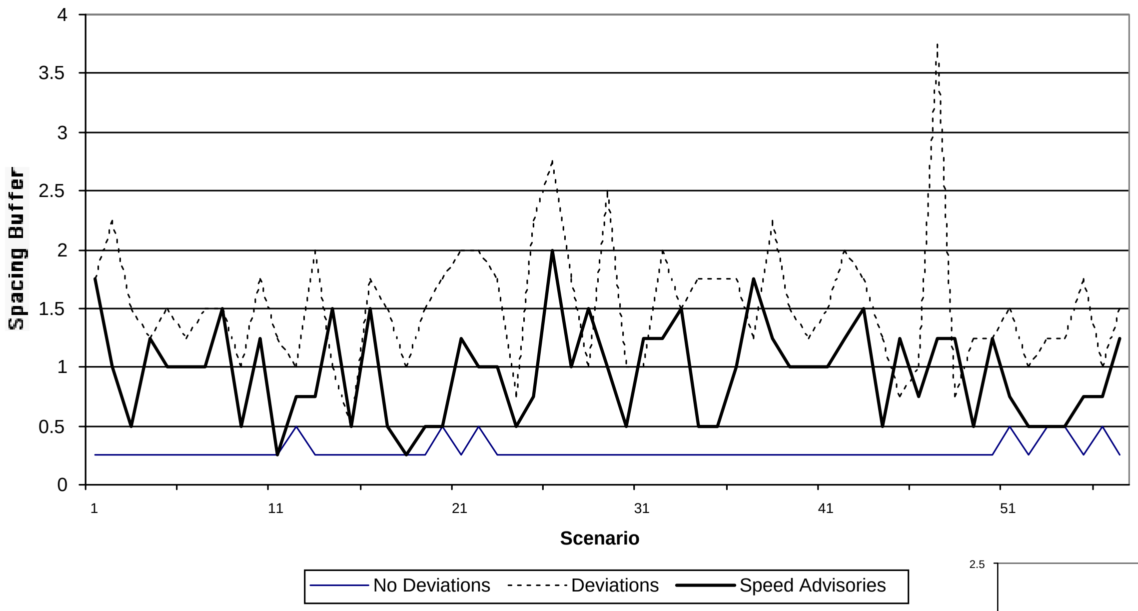
Front-Loaded Schedule

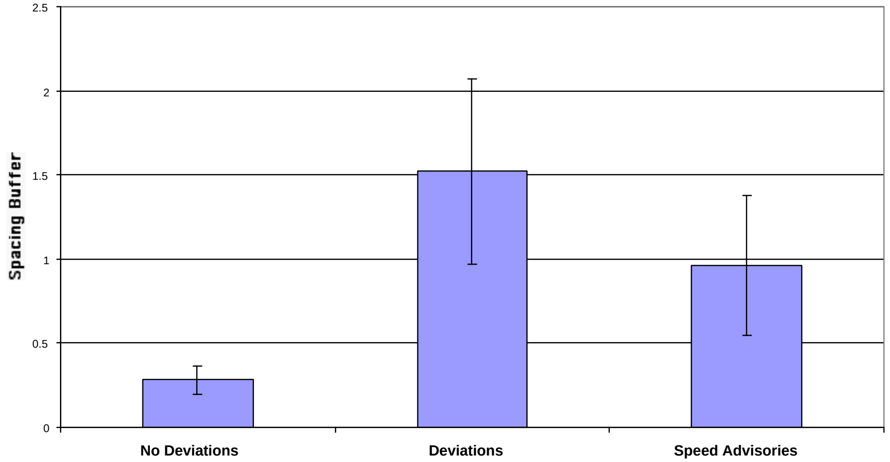




- Do speed advisories work better if there are more opportunities to use them?
  - 15 s front-loading

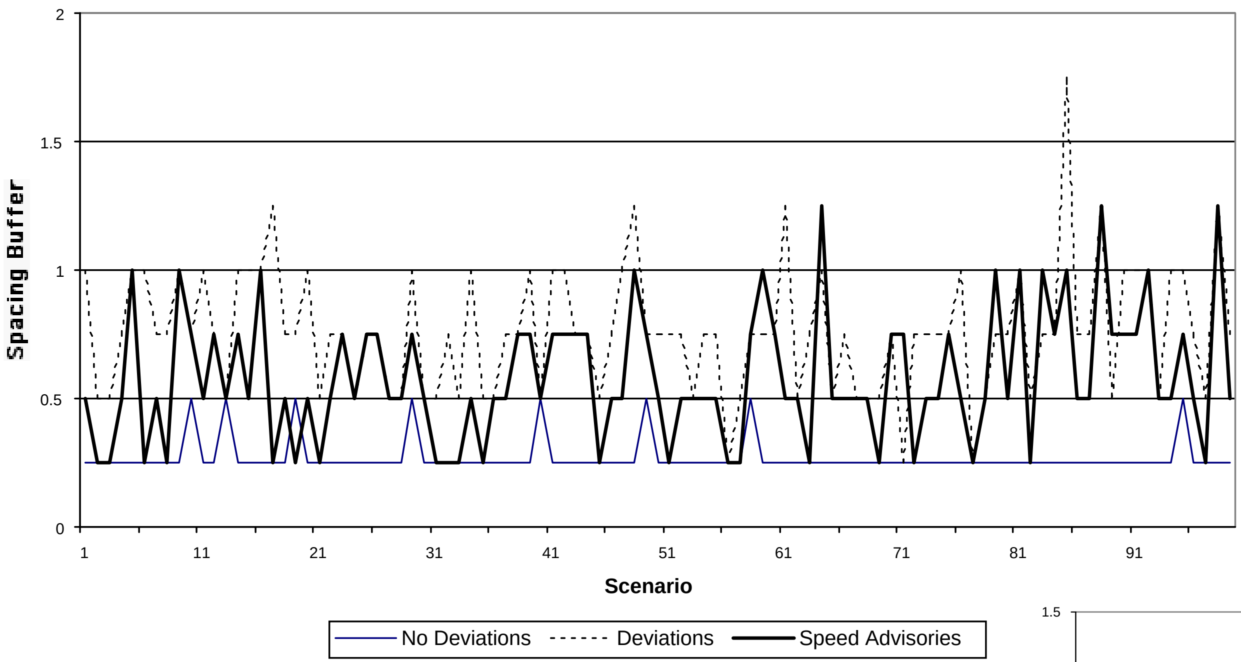
Acceleration Allowed

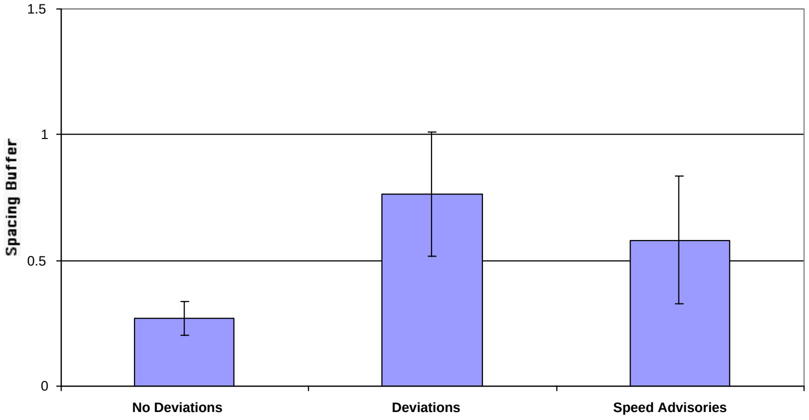




- 240 knots max
  - Limited to SW arrivals

Small Meter Fix Deviations





- N(0, 7.5), no landing speed deviation
  - Speed advisories *may* be enough

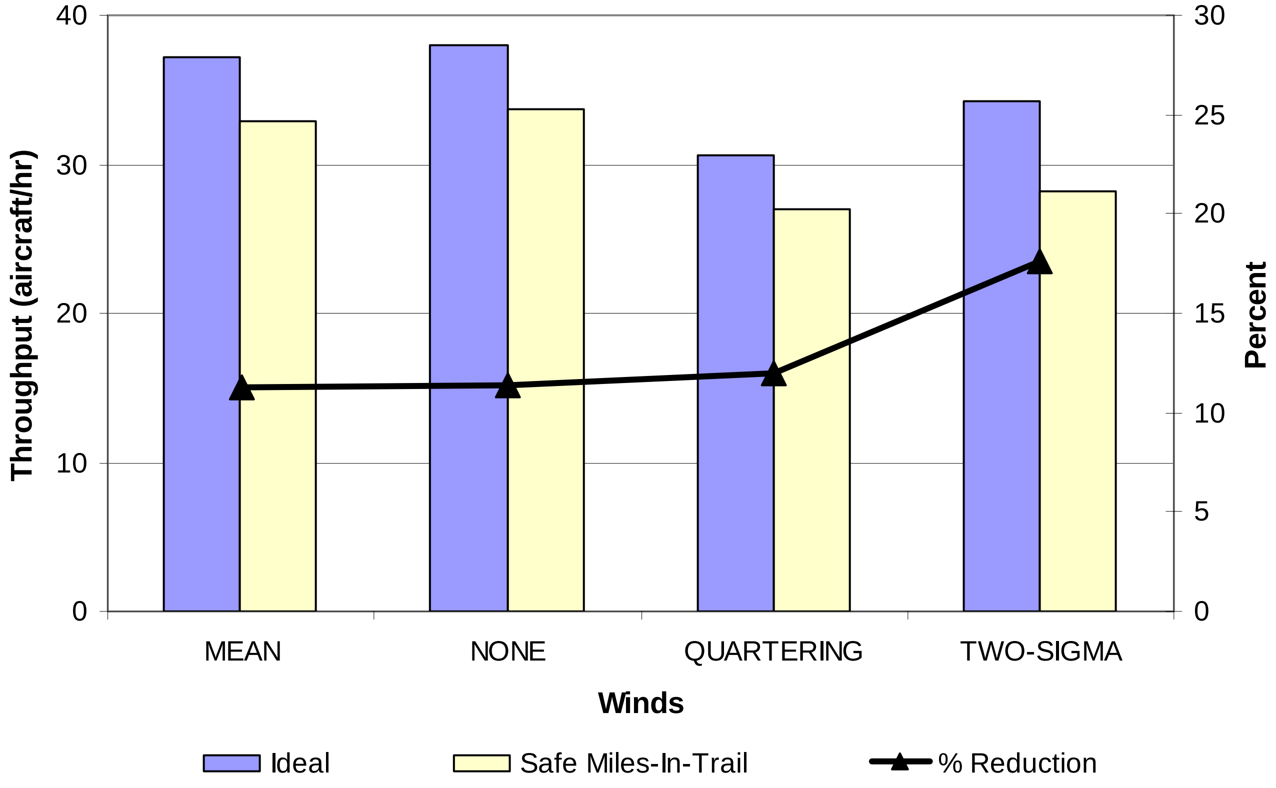
TCSim CDA Flow Set Up Results

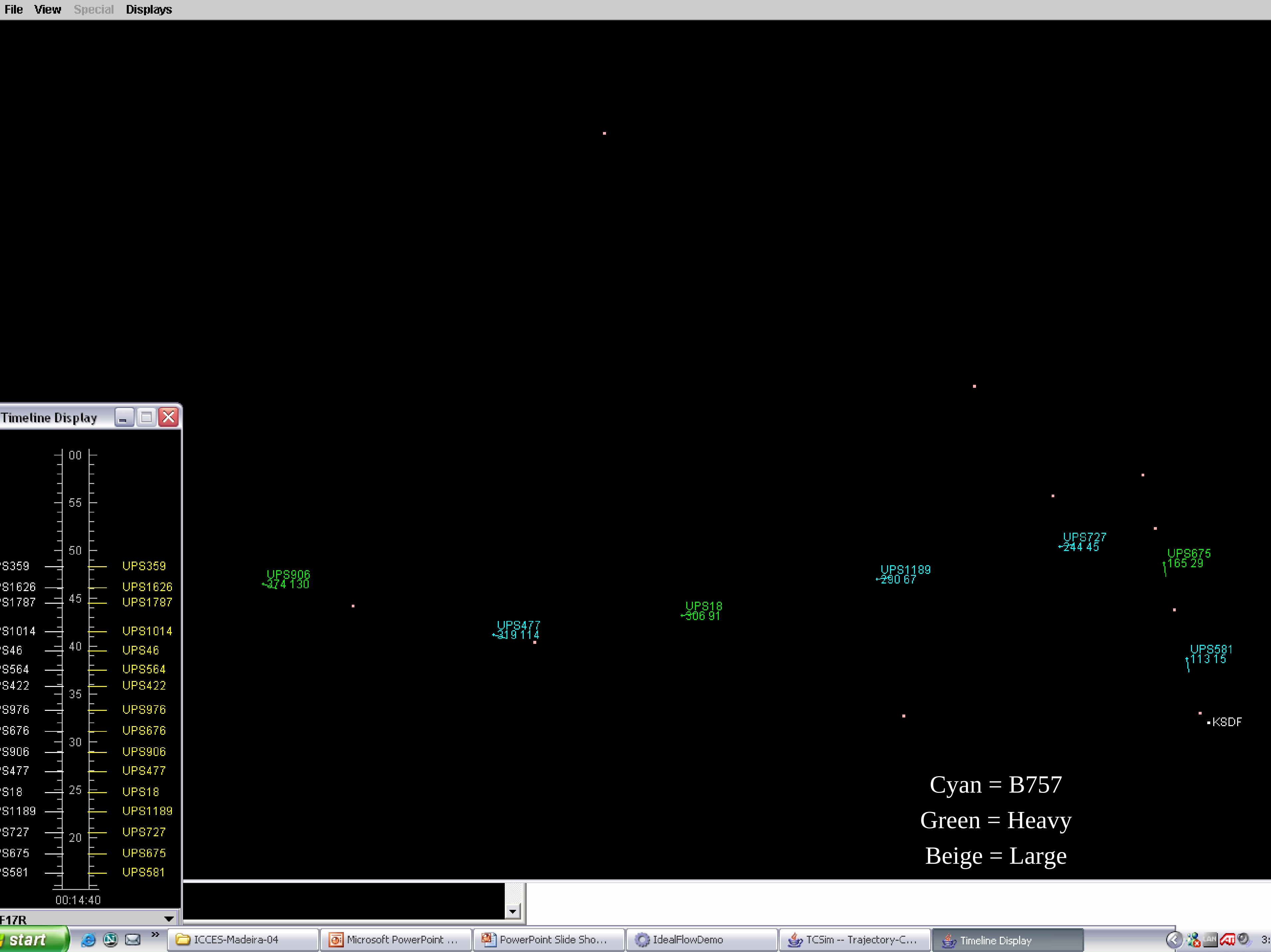
(2004 Flight Tests)

- Safe miles-in-trail spacing at CHERI for each wind condition
  - Requires no ATC intervention with CDA aircraft
  - Accounts for all possible wake vortex spacing pairs
    - DC8 following B767 is limiting case
  - Add additional buffer to values below to for setup errors

NONE	MEAN	TWO-SIGMA	QUARTERING
10	11	14	14

Safe Miles-in-Trail Capacity




File View Special Displays
Timeline Display
00
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00:14:40
UPS359
UPS1626
UPS1787
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UPS906
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UPS18
UPS1189
UPS727
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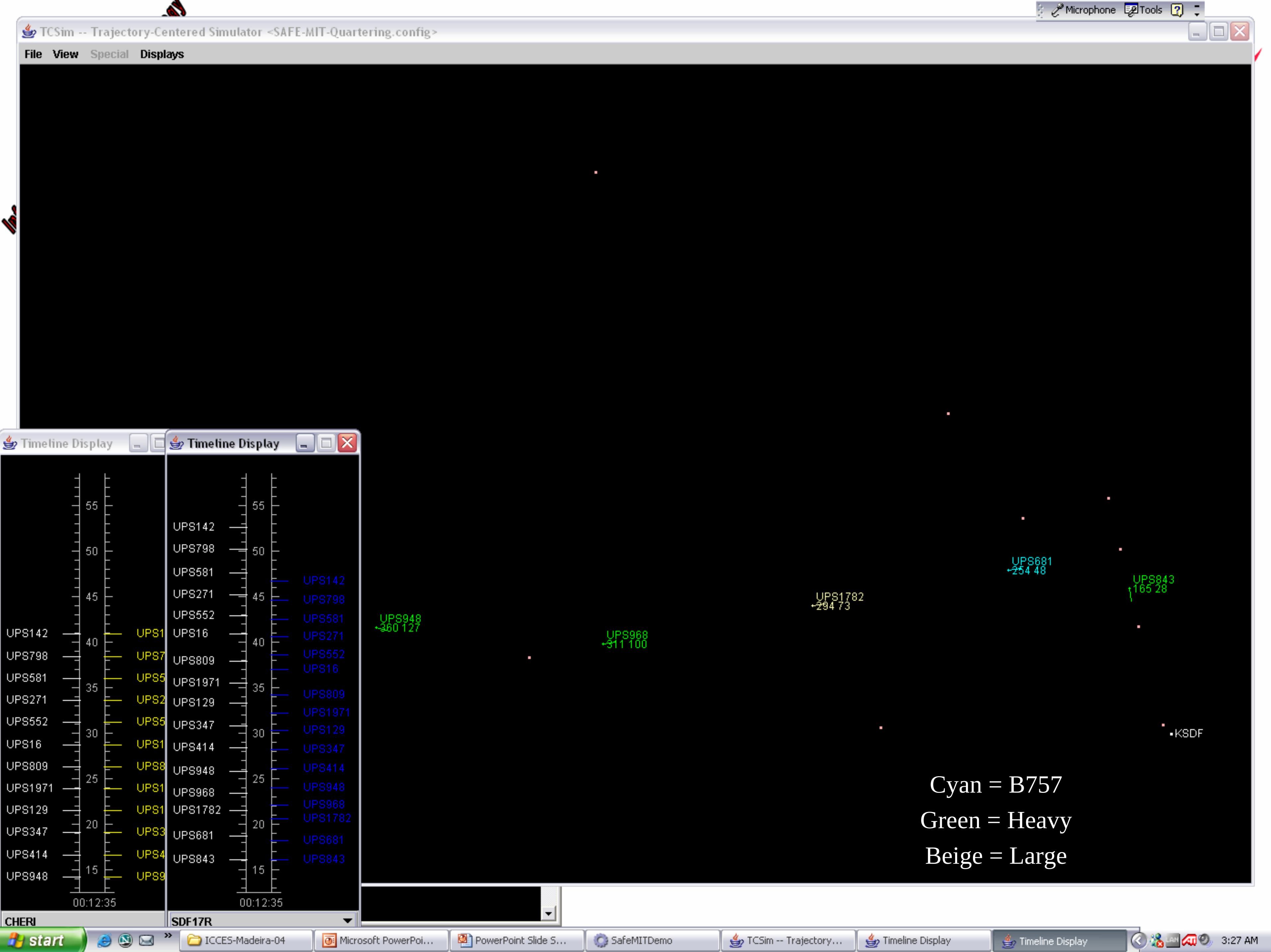
UPS581
F17R
UPS906
374 130
UPS477
319 114
UPS18
306 91
UPS1189
290 67
UPS727
244 45
UPS675
165 29
UPS581
113 15
KSDF
Cyan = B757
Green = Heavy
Beige = Large
start
ICCES-Madeira-04
Microsoft PowerPoint ...
PowerPoint Slide Sho...
IdealFlowDemo
TCSim -- Trajectory-C...
Timeline Display



Microphone
Tools
TCSim -- Trajectory-Centered Simulator <SAFE-MIT-Quartering.config>
File
View
Special
Displays
Timeline Display
Timeline Display
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30
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15
UPS142
UPS798
UPS581
UPS271
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UPS16
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UPS414
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CHERI
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UPS16
UPS809
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UPS414
UPS948
UPS968
UPS1782
UPS681
UPS843
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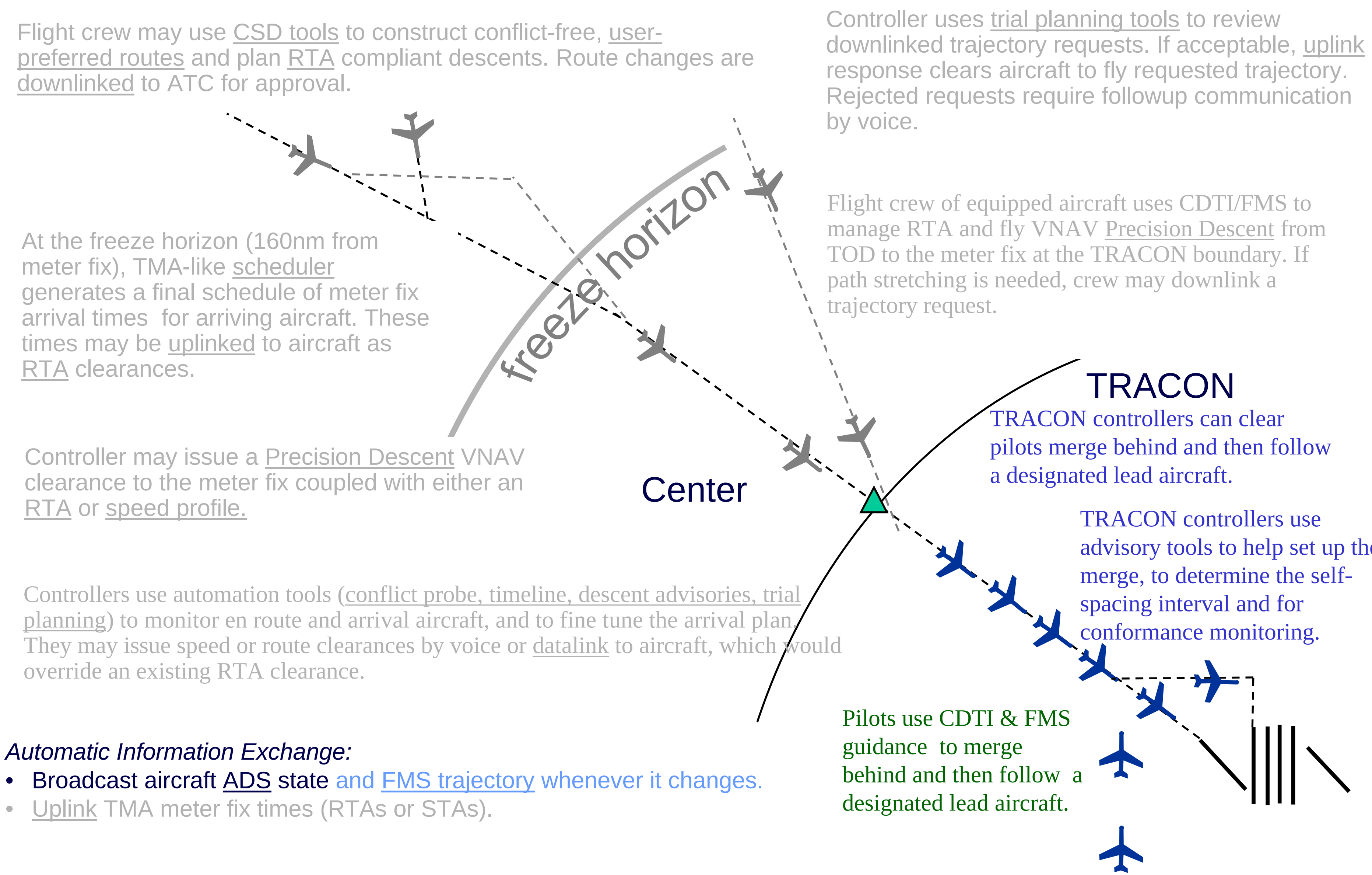
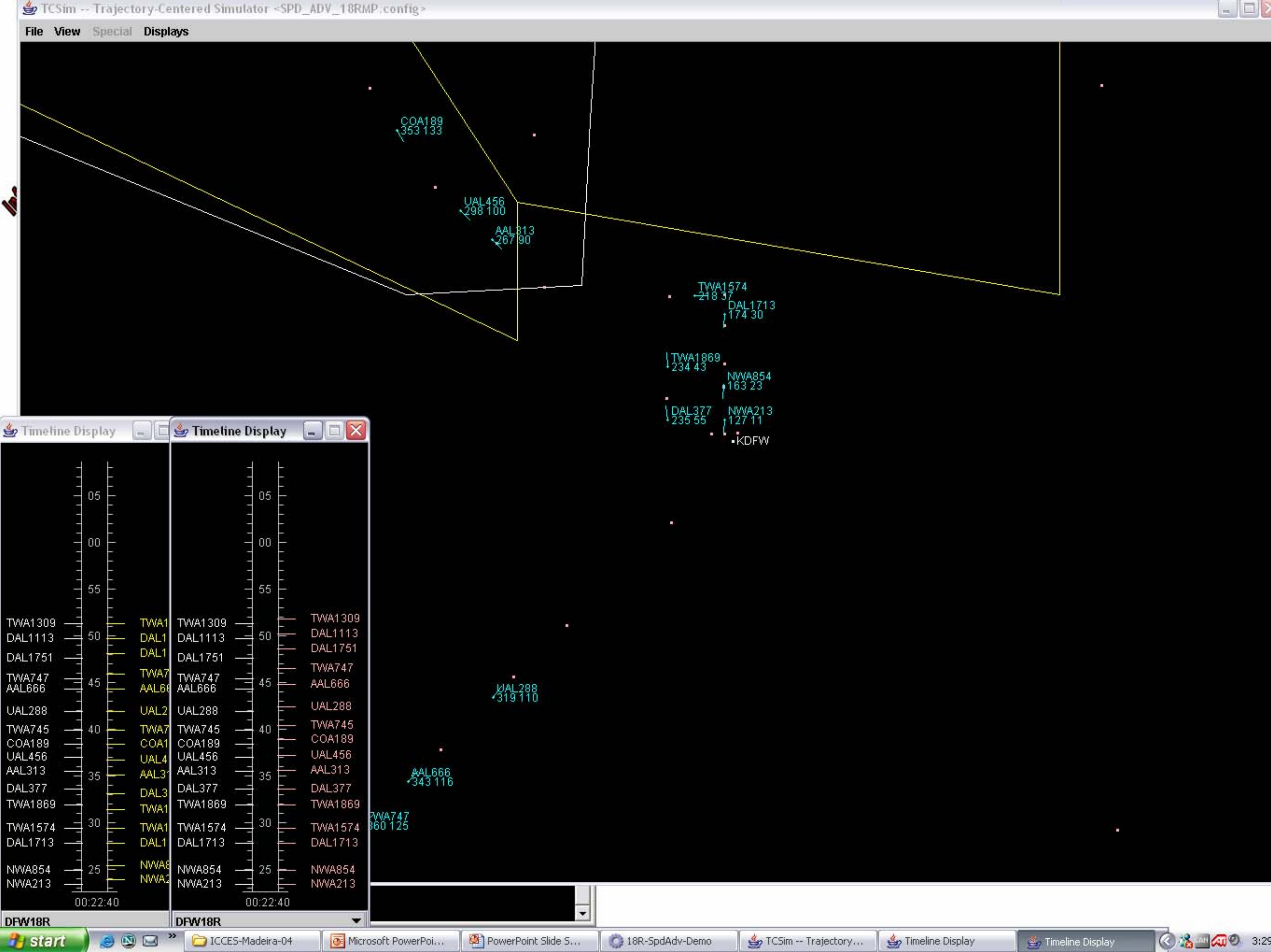
SDF17R
UPS948
360 127
UPS968
311 100
UPS1782
294 73
UPS681
254 48
UPS843
165 28
KSDF
Cyan = B757
Green = Heavy
Beige = Large
start
ICCES-Madeira-04
Microsoft PowerPoi...
PowerPoint Slide S...
SafeMITDemo
TCSim -- Trajectory...
Timeline Display
Timeline Display
3:27 AM

Scenario Events:
CE-11 TRACON Self-spacing





TCSim -- Trajectory-Centered Simulator <SPD_ADV_18RMP.config>
File View Special Displays
COA189 353 133
UAL456 298 100
AAL313 267 90
TWA1574 218 37
DAL1713 174 30
TWA1869 234 43
NWA854 163 23
DAL377 235 55
NWA213 127 11
KDFW
UAL288 319 110
AAL666 343 116
TWA747 360 125
Timeline Display
05 00 55 50 45 40 35 30 25
TWA1309 DAL1113 DAL1751 TWA747 AAL666 UAL288 TWA745 COA189 UAL456 AAL313 DAL377 TWA1869 TWA1574 DAL1713 NWA854 NWA213
00:22:40
DFW18R
Timeline Display
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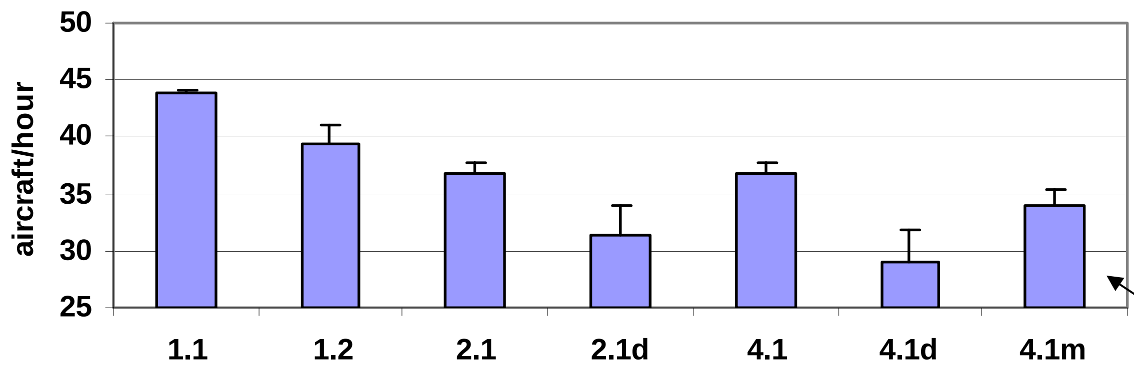
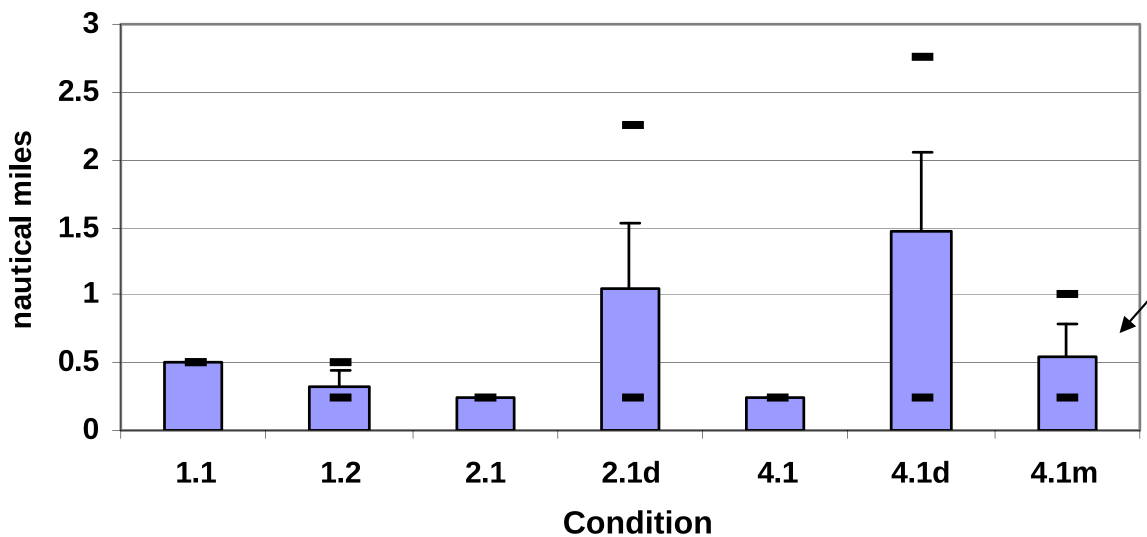
TWA1309 DAL1113 DAL1751 TWA747 AAL666 UAL288 TWA745 COA189 UAL456 AAL313 DAL377 TWA1869 TWA1574 DAL1713 NWA854 NWA213
TWA1309 DAL1113 DAL1751 TWA747 AAL666 UAL288 TWA745 COA189 UAL456 AAL313 DAL377 TWA1869 TWA1574 DAL1713 NWA854 NWA213
00:22:40
DFW18R
start
ICCES-Madeira-04
Microsoft PowerPoi...
PowerPoint Slide S...
18R-SpdAdv-Demo
TCSim -- Trajectory...
Timeline Display
Timeline Display

Example Results from Applying Analysis Methodology with 'Planning Agents'

Throughput



Additional Spacing Buffer



Impact of speed advisory clearances

Future Research Directions I

- Controller strategy-tool interactions
- Constraint representation
- Workload assessment

ATC Strategies

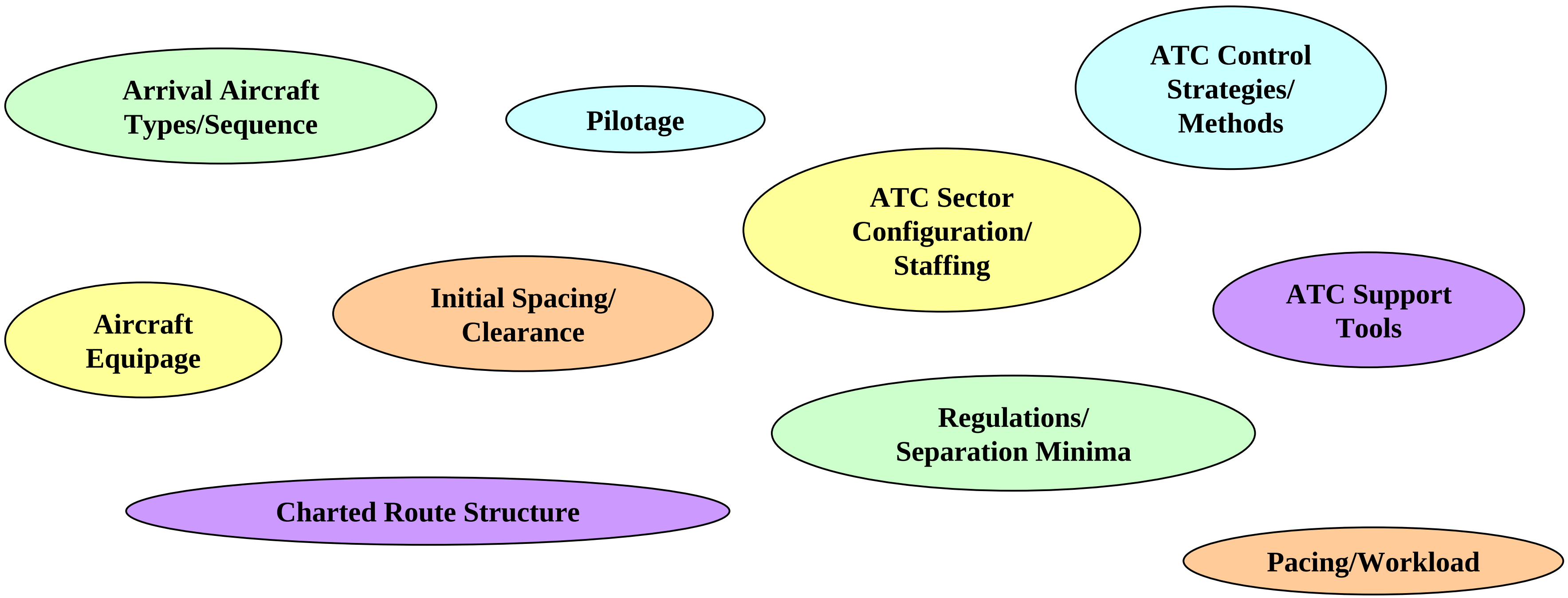
- Crucial for action prioritization
  - Control solutions ('vectors first')
  - Problem simplification and workload management ('match speeds')
  - Addressing conflicts ('head-on's first')

- What strategy-tool combinations are suitable for controlling traffic with particular characteristics?

- Under what conditions (i.e., what combinations of factors such as wind-prediction errors beyond a certain limit or initial traffic spacing less than some amount) do particular strategies cease to be effective?

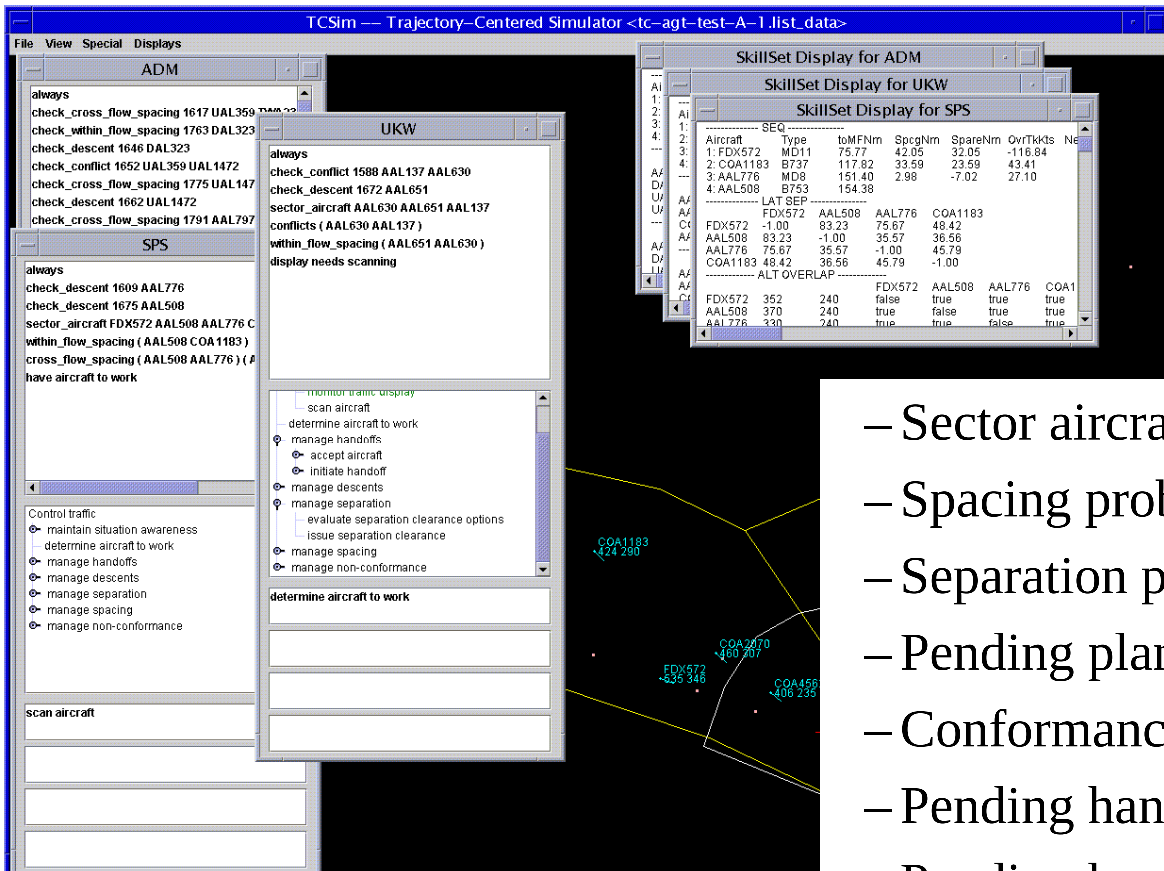
- Can air traffic controllers revert to current operations smoothly as the situation warrants (i.e., is the system robust to the full range of conditions that may arise)?

Constraints



- Realistic ATC agents…
  - Maintain ‘picture’ that captures dynamic constraints
  - Respond intelligently to them

Workload Measures



Workload = weighted function of:

- Sector aircraft
- Spacing problems
- Separation problems
- Pending plans and differences in plans
- Conformance monitoring problems
- Pending handoffs
- Pending handoff accepts
- ...

Further research II

- Controller agent validation studies using CE11 controller performance data
- Disturbance models
- Operational errors and safety/risk assessment
- Integration with related work

Conclusion

- Simulating air traffic controller and automation performance can shed light on new air traffic management concepts and complement human-in-the-loop research

- Additional research is required to model how controllers adapt strategies to maintain safety while satisfying a range of task demands in the face of environmental disturbances