Estimating Airspace Capacity based on Risk Mitigation Metrics

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Outline

• Research Objectives and Background

• Research Approach

• Metrics Definition and Estimation

• Capacity under Human Control in Current Operations

• Capacity under Automation Assisted Control

• Conclusions and Insights

• Future Extensions
• Future air transportation systems introduce major changes to air traffic operations, for example
  – *Automation assistance to service providers*
  – *Mixed levels of navigation and communication performance*
  – *Different distribution of responsibilities between service providers and flight operators*

• Research objective: Develop foundational and generic metrics to estimate airspace capacity that are applicable to current and future operations

• Preliminary exploratory research effort funded by NASA
Many approaches have been attempted to estimate airspace capacity, mainly focusing on measuring traffic complexity representing controller workload.

Few examples include:

- Maximum operationally acceptable aircraft count
- Dynamic density
- Traffic entropy
- Clustering techniques
- Cognitive indicators
Research Approach

• In this research two key elements were considered in order to derive generic capacity metrics

  – (1) Tying airspace capacity to ability to mitigate risk of violating traffic management constraints
    • Any control scheme has to maintain safe and efficient operations

  – (2) Accounting for cognitive factor in determining capacity
    • Airspace capacity is dependent on control strategy and its risk
    • Attempted to quantify risk tolerance in control strategy
    • Control strategy may represent current or future control schemes: human control, automation control, automation assisted control, static or dynamic configuration of airspace and flow structures, etc.
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Airspace Capacity Metrics

• Capacity metrics defined based on traffic flow notions
  – *Airspace sector has service rate to transit aircraft through it*
  – *Airspace sector has capacity to hold aircraft*

• Several possible inter-related measures
  – *Throughput capacity: Maximum number of aircraft that can transit airspace sector in unit time*
  – *Capacity to hold aircraft: maximum number of aircraft that can be stacked and held in airspace sector at one time*
  – *Capacity to delay aircraft: Maximum amount of delay that can be absorbed in airspace sector for a flight*
Airspace Capacity Metrics

• Capacity limits depend on control strategy, for example
  – *Throughput capacity is higher if aircraft travel with higher speed limits, with less separation, and in segregated flows*
  – *Capacity to hold aircraft is higher with holding patterns*
  – *Capacity to delay aircraft is higher with more degrees of freedom, such as speed reduction and S-turns*

• Future concepts may increase capacity through more efficient control strategies
  – *Automation assistance, dynamic airspace configuration, …*
Risk Mitigation Metrics

• Capacity is limited by tolerance of control strategy to constraint violation risk

• Defined risk tolerance of control strategy as probability of selecting feasible trajectory according to strategy

• Several possible metrics, one used in paper:
  
  – Number of feasible trajectories (called Adaptability – ADP for short)
    
    • Strategy provides $f_c(t, x, y, z)$ feasible trajectories at point $(t, x, y, z)$ given known constraint set $C$ ($f_c$ can be expected value over distribution of $C$)
    
    • $f_c$ represents ability to adapt to any risk of constraint violation by selecting feasible trajectory from available ones, or
    
    • $1/f_c$ represents probability of losing feasibility due to risk of constraint violation
Risk Mitigation Metrics Estimation

Reachability $g_k(x,y) = \text{number of trajectories from point } k \text{ to each cell } (x,y), \text{ using discrete heading and speed values held constant over time step } \varepsilon$

Find number of feasible trajectories $f_c$ from Point $k$ to destination

Grid of discrete $x$-$y$ cells

Blocked cells due to loss of separation

0's

Destination (RTA with tolerance)

Initialization of last time step: $f=1$ if inside RTA tolerance, $f=0$ if outside

$0$'s

Time step $\varepsilon$

$f_c(k)$ is derived by multiplying $g_k(x,y)$ and $f_c(t,x,y)$

Control strategy represented in discrete decision tree for trajectory planning to estimate $f_c$ at each point in time and space ($t$, $x$, $y$, $z$) – e.g., to meet required time of arrival (RTA)
Risk Mitigation Metrics Estimation

Example discrete solution space with adaptability values at each location

- Blocked solutions due to constraints (other aircraft)
- Trajectory tracing maximum adaptability
- Destination point with RTA constraint

![Diagram showing a 3D plot with axes labeled X, Y, and time, and a color scale labeled Log(ADP).]
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Historical Data Analysis Methodology

• **Identified human control strategy for absorbing delay in arrival metering situation through interview**

• **Selected airspace sectors with traffic control behavior similar to elicited human control strategy**
  – **Airspace sectors with metering of arrivals to congested airports**

• **Identified adaptability-capacity tradeoff for selected sectors**
  – **Capacity measured as maximum ability to absorb delay**
  – **Adaptability measured as number of feasible trajectories to absorb required delay and avoid other traffic trajectories**

• **Used ASDI track data from May-June 2004 (32 days)**
Human Control Strategy

Human delay absorption behavior based on controller interview:

Absorb delay when aircraft are lower and slower (closer to meter fix)
Reduce degrees of freedom by coupling aircraft in string

Dominant wind direction

Path stretch under low delay
Path stretch under high delay
Nominal string of aircraft
Path stretch starting earlier
Turn out angle 60-70 degrees
Merging into single stream

Meter fix
Sector boundary
Human Control Strategy

Human delay absorption behavior based on controller interview:

As delay increases start descent earlier → More level off at lower altitude → More controllability but less fuel efficiency

Nominal descent without delay

Earlier descent to 270 with higher delay

Risk of increased level off at FL 270

Increased level segment at FL190

Low sector FL 190-270

High sector FL 270-350

Earliest descent to 190 with higher delay

Meter fix
Human Control Strategy

Human delay absorption behavior based on controller interview:

<table>
<thead>
<tr>
<th>Delay</th>
<th>High sector</th>
<th>Low sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2 minutes</td>
<td>Do nothing</td>
<td>Use speed to absorb delay: Either drop to 250 knots at appropriate time to meet RTA, or drop speed in couple steps to 265 and then to 250 knots</td>
</tr>
<tr>
<td>3 minutes</td>
<td>Do nothing</td>
<td>Use path stretch while descending</td>
</tr>
<tr>
<td>4-7 minutes</td>
<td>Drop speed to 250 knots</td>
<td>Use path stretch</td>
</tr>
<tr>
<td></td>
<td>Establish sequence in trail</td>
<td>The larger the delay the sooner altitude is dropped to 190, to allow more control using path stretch when aircraft is lower and slower by increasing level segment at 190</td>
</tr>
<tr>
<td></td>
<td>Drop altitude earlier than usual to 270,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>providing aircraft to low sector earlier to allow low sector more time and control</td>
<td></td>
</tr>
<tr>
<td>More than 7 minutes</td>
<td>Do not absorb delay nor sequence</td>
<td>Hold aircraft: Holding is used to absorb full amount of delay. Exit from holding pattern is manipulated such that amount of travel time remaining after exiting the hold meets RTA</td>
</tr>
<tr>
<td></td>
<td>Descend aircraft to altitudes stacked by 1000 feet 270&gt;280&gt;290... in anticipation of holding at these altitudes if there is holding overflow from low sector</td>
<td></td>
</tr>
</tbody>
</table>
Sector Selection

- Various traffic patterns observed – Visualized flight plan and track data using FACET and MATLAB
Sector Selection

• ZAU74 and ZAU26 selected for analysis
  – ZAU26 small sector with single stream and merge in upstream sector
  – ZAU74 large sector with single stream and merge inside sector
Human Control Strategy Observations

- Path stretch to absorb moderate delay
  - Variation variation in merge point
  - Path stretch mainly to one side
  - Path stretch start point and magnitude vary
  - Path stretch starts mainly after merge

Exit point has large tolerance

ZAU74
One day traffic

ZAU26
One day traffic
• Holding strategy applied to absorb high delays when path stretch is not sufficient

Holding patterns

ZAU26
One day traffic

ZAU74
One day traffic
Adaptability versus Capacity Analysis

- Delay estimated for each flight relative to unimpeded travel

  - **Unimpeded travel**
    - Time estimated using initial speed along straight line between entry and exit points
  
  - **Held aircraft**
    - Identified by detecting loop in trajectory

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Estimating Airspace Capacity based on Risk Mitigation Metrics

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Adaptability versus Capacity Analysis

• ADP estimated for each flight using discrete decision tree:
  
  – *Actual duration of flight in sector as desired time to meet at meter fix*
  
  – *Flight enters sector at actual boundary crossing*
  
  – *Flight allowed to exit at exit fix with 3 mile tolerance*
  
  – *Flight to absorb delay by path stretching to one side and speed reduction*
  
  – *Merging point, path stretch start and magnitude are degrees of freedom*
  
  – *Three most frequent speeds allowed*
  
  – *Solutions that lose separation with other traffic actual trajectories removed*
  
  – *2-D 1x1-mile cells and 1-minute time steps*
Adaptability versus Capacity Analysis

• ADP plotted versus delay to show tradeoff and limits

ADP reaches maximum value → indicating more risk adaptability at moderate delay level

Smaller sector has less adaptability and capacity

ADP low at low delay → indicating limited capacity for unimpeded travel

ADP drops at high delay → indicating limited capacity to absorb delay
Adaptability versus Capacity Analysis

• Switching to holding as indication of reaching capacity limit of path stretch control strategy as perceived by controllers

  – **Holding starts earlier**
    for smaller sector ZAU26
  
  – **Controllers switched to holding at relatively high ADP values**
    where path stretching still had many solutions

![Graph showing adaptability and holding ratio over delay in minutes for ZAU74 and ZAU26 sectors.](image)
Adaptability versus Capacity Analysis

- Larger sector ZAU74 switched to holding at higher ADP relative to smaller sector ZAU26

Observation: Controllers may not use all available sector area for path stretch before holding.
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Automation Control Strategy

Example automation algorithm for delay absorption:

Starting path stretch higher → Continuous descent benefits
No merging or coupling → Less organized traffic
More degrees of freedom
Simulation Analysis

- Human control scenario simulated in MATLAB
  - Two dimensional rectangular airspace with metering at fix
  - Steady state flow: Aircraft enter and leave at two minute intervals
  - Aircraft introduced at random locations equidistant from fix
  - Aircraft merged on single centerline within prescribed location window
  - Each aircraft used speed and path stretch to one side to absorb assigned delay (relative to fastest time) and avoid preceding aircraft trajectories

Example trajectories

Delay = 8; Maneuver freedom = Heading + Turnout + Speed
Simulation Analysis

• Human control scenario simulated in MATLAB
  
  – Aircraft computed trajectory to absorb delay and maximize ADP
  
  – Path stretch to one side only after merge; decision variables:
    
    • Merge point, turn out point, angle, and amount of path stretch
    
    • Speed profile – Three speed step-down 300, 270, 240 knots
  
  – Delay increased until no solution exits to identify capacity to absorb delay
Simulation Analysis

• Automation assisted control scenario simulated in MATLAB
  
  – Differences with human control strategy highlighted in red
  
  – Two dimensional rectangular airspace with metering at fix
  
  – Steady state flow: Aircraft enter and leave at two minute intervals
  
  – Aircraft introduced at random locations equidistant from fix
  
  – Aircraft not merged on single centerline
  
  – Each aircraft used speed and path stretch to either side to absorb assigned delay (relative to fastest time)
  
  and avoid preceding aircraft trajectories

Example trajectories
Simulation Analysis

• Automation assisted control scenario simulated in MATLAB
  – *Aircraft computed trajectory to absorb delay and maximize ADP*
  – *Path stretch to either side and from entry point; decision variables:*
    • Side, turn out point, angle, and amount of path stretch
    • Speed profile – Three speed step-down 300, 270, 240 knots
  – *Delay increased until no solution exits to identify capacity to absorb delay*
Adaptability versus Capacity Analysis

• Indication of capacity using ADP
  – Similar trend to historical data analysis
  – Theoretical capacity limits can be inferred at zero ADP
  – More delay can be absorbed relative to human control strategy because of increased degrees of freedom
    • path stretching earlier and to both sides
Adaptability versus Capacity Analysis

• Indication of capacity using ADP
  – *ISO-ADP curve can be drawn at desired risk mitigation level*
    • e.g., ADP level perceived by controller from historical data analysis
  – *ISO-ADP curve traces corresponding capacity limits under different control strategies*
    • Similar ADP values reached at higher delay capacity under automation strategy
  – *Higher ADP achieved by automation strategy at similar capacity limits*
    • Automation can consider more solutions to mitigate risk
    • However, human may not be able to if automation failed

![Graph showing Adaptability versus Capacity Analysis](image-url)

- Log (ADP) vs. Delay
- Manual and Automation comparisons
- Average ADP over 10 aircraft
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Conclusions and Insights

• Adaptability, and risk mitigation metrics in general, have potential to help estimate airspace capacity

  – Theoretical capacity limits can be determined where adaptability approaches zero indicating no solutions to mitigate constraint violation
  – Practical capacity limits can be determined, e.g., where adaptability is highest or at some desired threshold above zero
  – Controller behavior exhibited tradeoff between adaptability and capacity where controller perceived capacity at relatively high adaptability levels
  – Tradeoffs between adaptability and capacity can be quantified under different factors such as airspace size and number of degrees of freedom
  – Capacity and adaptability gains and tradeoffs can be quantified and compared between alternative, current and future, control schemes
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Future Research Extensions

• Further validation and identification of controller risk tolerance and capacity perception by analyzing larger sets of airspace resources and traffic control strategies

• Application to quantify capacity-risk tradeoffs under different future concepts including automation, airspace configuration, distribution of responsibilities

• Analysis of capacity-risk tradeoffs under off-nominal conditions, e.g., automation failure and transition to human control
Risk Mitigation Metrics Estimation

- Discrete decision tree to estimate $f_c$
  - *Time, space and degrees of freedom* assume discrete values within limits
  - *Trajectory is series of reachable cells*
  - *Reachability and number of trajectories* estimated from center of each cell ($k$)
  - *Reachable points within cell counted and recorded into a reachability function $g(k)$, assuming constant values of degrees of freedom between time steps*
  - *Sizes of time step and cell represent sampling resolution for estimating number of trajectories*
Metrics Definition and Estimation

- **Trajectory Planning**: Dynamic program back-propagation (recursion)

\[ Q(t, x(k), y(k)) = \min_{x,y: g_k(t+1, x, y) = 1} \{ Q(t+1, x, y) + q(k \rightarrow (t+1, x, y)) \} \]

1. Initialize cost at final time step
2. Find and store best cost \( Q \) over reachable states
3. Repeat (2) for each cell
4. Starting from initial cell trace optimal path already stored, breaking ties randomly

Reachability of point \( k \) over \( \varepsilon \) given by \( g_k \)
Risk Mitigation Metrics

- Using flexibility metric implicitly reduced traffic complexity

Scenario: Opposite traffic through weather cells
Flexibility: unidirectional flow through holes

Scenario: Round about
Flexibility: 97% counterclockwise (blue)
Shortest path: 60% counterclockwise
Adaptability versus Capacity Analysis

- Switching to holding as indication of reaching capacity limit of path stretch control strategy
  - Saturation of throughput coincides with switching to holding
  - Holding applied when throughput is reduced
Human Control Strategy Observations

- Example speed and altitude profiles

**ZAU26**

**ZAU74**
Adaptability versus Capacity Analysis

- One reason for lower ADP is the number of other traffic that eliminates solutions
  - Number of other traffic larger at higher delays

![Graph showing relationship between Number of Intruder Aircraft and Delay](image-url)