The Centre for Transport Studies
Imperial College London:
Developments in measuring airspace capacity in Europe

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Content

• The en-route capacity problem
  – estimation difficulties

• Three research projects
  – a framework for estimating en-route airspace capacity
    ➢ RAMS simulation
    ➢ capacity curve
  – multivariate analysis of factors affecting controller workload
    ➢ CAPAN/ EAM simulations
    ➢ principal components and factor analysis
  – cross-sectional time-series analysis of controller workload
    ➢ RAMS simulation
    ➢ panel data analysis
The En-Route Capacity Estimation Problem
The Airspace Congestion Problem

• Rapid growth in air traffic in Europe & USA:
  – Consequences, e.g. US$ 5bn.
  – predicted traffic growth;

• Airspace capacity needs to be increased:
  – en-route controller workload

• New CNS/ATM concepts
  - new technologies and procedures, e.g. direct routes

There is a need to:
• Understand the drivers of airspace capacity;
• Develop a consistent method to estimate airspace capacity.
What makes en-route capacity different?

The controller workload problem!
Controller workload reduces max theoretical cap.
Three questions on controller workload

– What is controller workload?
  ➢ Confusing term.

– How is it measured?
  ➢ Many methods.

– What is an acceptable level?

Lyons and Shorthose (1993): shortcomings of capacity measures
## Classification scheme for capacity

<table>
<thead>
<tr>
<th>Perceived Workload Estimates</th>
<th>Measured Workload Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Declared Capacity</td>
<td>MBB Method</td>
</tr>
<tr>
<td>MACE Capacity Estimate</td>
<td>Task Time Methods</td>
</tr>
<tr>
<td>FAA Order 7210.46</td>
<td>“Schmidt” Workload Model</td>
</tr>
<tr>
<td>Air/Ground Communications Link*</td>
<td>The CARE-INTEGRA method</td>
</tr>
</tbody>
</table>

* Workload measured indirectly by Air/ground communications link method.
Current situation

• En-route controller workload:
  – determines en-route sector capacity

• Current capacity estimation:
  – controller workload simulation;
  – workload threshold value.

Sector Capacity:
No. of aircraft entering the sector per hour, respecting the peak hour pattern, when controller workload is 70% in that hour.
The problem - I

- Sector entry is the only variable:
  - considerable dispersion.
The problem - II

- What about other variables?
  - possible relationships;
  - additional effects;
  - univariate vs. multivariate.
The problem - III

• Airspace capacity defined by sector entry
  ➢ Useful BUT
  ➢ Considerable variance.

• Need to consider other variables?
  ➢ Interactions;
  ➢ Quadratic effects.

Three studies on airspace capacity at CTS provide insights into capacity estimation
A framework for estimating airspace capacity using RAMS
Plan

Estimation of en-route capacity of Europe:

• simulation modelling
  - RAMS;
  - methodology;

• workload
  - factors;
  - analysis;

• capacity curves
Airspace Capacity Again

Airspace Capacity depends upon controller workload

i) \( C = tW \)

\( C \) = Airspace capacity
\( t \) = threshold
\( W \) = controller workload

ii) \( W = f(X) \)

\( X \) = factors affecting workload

• Analyse factors affecting workload;
• Then determine impact on capacity.
What affects controller workload?

**FACTORS AFFECTING CONTROLLER WORKLOAD**
Source: Mogford et al. (1995), page 5
## Literature on variables affecting workload

Previous research indicates:

<table>
<thead>
<tr>
<th>Air Traffic Factors</th>
<th>Sector Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of aircraft</td>
<td>Sector size</td>
</tr>
<tr>
<td>Peak hourly count</td>
<td>Sector shape</td>
</tr>
<tr>
<td>Traffic mix</td>
<td>Boundary location</td>
</tr>
<tr>
<td>Climbing/descending aircraft</td>
<td>Number of intersection points</td>
</tr>
<tr>
<td>Aircraft speeds</td>
<td>Number of flight levels</td>
</tr>
<tr>
<td>Horizontal separation standards</td>
<td>Number of facilities</td>
</tr>
<tr>
<td>Vertical separation standards</td>
<td>Number of entry and exit points</td>
</tr>
<tr>
<td>Average flight duration in sector</td>
<td>Airway configuration</td>
</tr>
<tr>
<td>Total flight time in sector</td>
<td>Proportion of unidirectional routes</td>
</tr>
<tr>
<td>Average flight direction</td>
<td>Number of surrounding sectors</td>
</tr>
</tbody>
</table>
Why RAMS?

• RAMS not overtly cognitive, but:
  - captures observable tasks
  - also mental tasks e.g. resolution
  - workload thresholds - controller based

• RAMS:
  - > 25 years use in European airspace planning

• Controller:
  - task input
  - realistic conflict detection and resolution
  - simulation & output verification
En-Route Capacity Estimation I

**INPUTS**

- **SECTOR**
  - Sector corner points
  - Sector boundaries
  - Number of flight levels
  - Number of navigation aids
  - Number of airports

- **AIR TRAFFIC**
  - Aircraft type
  - Aircraft performance
  - Flight plan of aircraft
  - Rules for "cloning" aircraft

- **CONTROLLER TASKS**
  - Controller tasks
  - Task categories
  - Task timings
  - Conflict resolution strategies

**OUTPUTS**

- **FLIGHT HISTORY**
  - Actual flight profiles flown
  - ATC interventions to flights

- **WORKLOAD**
  - Workload recorded for controlling each flight, per controller
  - Workload discriminated by category

- **CONFLICT HISTORY**
  - Aircraft involved in conflict
  - Type of conflict
  - Resolution applied

**RAMS**

Simulation model
En-Route Capacity Estimation II

Main features of simulation:

- Traffic levels varied systematically
  - Current (1996) base traffic;
  - Future traffic.

- 122 ATC sectors
  - Continental European airspace

- Bordeaux Task Base

- Sectors at capacity rules:
  - “Nominal” capacity
Capacity Estimation - Analytical Procedures

Prior Studies

Ordinary Least Squares (OLS)

Assumptions

Interaction terms

Test for variance in data

Test for spatial autocorrelation

Spatial autocorrelation present

Estimation Methods

Estimated Generalised Least Squares (EGLS)

Covariogram

Maximum Likelihood (ML)

RAMS OUTPUT

WORKLOAD

AIRCRAFT ATTITUDE

Consequences

Assumptions
En-Route Capacity Estimation III

RAMS output:
- Workload;
- Flight history.

Functional model formulation:
- OLS;
- Test assumptions;
- Maximum Likelihood.

Spatial correlation:
- Estimation;
- Variogram.
Factors that affect controller workload:

- Cruise;
- Ascend;
- Cruise$^2$;
- Descend x Cruise;
- Ascend x Cruise;
- Descend x Ascend.
# Results

## Current Demand Pattern - WLS

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter</th>
<th>SE</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>148.54</td>
<td>54.73</td>
<td>2.71</td>
</tr>
<tr>
<td>Cruise</td>
<td>56.95</td>
<td>6.25</td>
<td>9.11</td>
</tr>
<tr>
<td>Ascend</td>
<td>46.54</td>
<td>8.527</td>
<td>5.46</td>
</tr>
<tr>
<td>Cruise²</td>
<td>-0.57</td>
<td>0.069</td>
<td>-8.26</td>
</tr>
<tr>
<td>Descend x Cruise</td>
<td>4.27</td>
<td>0.746</td>
<td>5.73</td>
</tr>
<tr>
<td>Ascend x Cruise</td>
<td>1.67</td>
<td>0.634</td>
<td>2.62</td>
</tr>
<tr>
<td>Descend x Ascend</td>
<td>4.98</td>
<td>0.947</td>
<td>5.26</td>
</tr>
<tr>
<td>Adjusted $R^2$</td>
<td>0.9241</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

N.B. Surface uses Bordeaux Task Base
The Capacity Curve
For current ATC/ATM environment
The Capacity Curve - Uses

What does the capacity curve predict?
- **Number of descending traffic in declared sectors**

<table>
<thead>
<tr>
<th>Sector</th>
<th>DECLARED TOTAL</th>
<th>Declared</th>
<th>Diff. WLS (+)</th>
<th>Diff. MLE (+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maastricht</td>
<td>51</td>
<td>12.8</td>
<td>3.1</td>
<td>4.1</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>41</td>
<td>6.2</td>
<td>12.8</td>
<td>14.3</td>
</tr>
<tr>
<td>Munich</td>
<td>36</td>
<td>12.6</td>
<td>20.2</td>
<td>21.5</td>
</tr>
<tr>
<td>Milan</td>
<td>41</td>
<td>11.1</td>
<td>13.4</td>
<td>15.5</td>
</tr>
<tr>
<td>Reims</td>
<td>28</td>
<td>1.1</td>
<td>27.1</td>
<td>29.5</td>
</tr>
</tbody>
</table>

N.B. Cruise and Ascend traffic same as declared
Conclusion

A framework to estimate airspace capacity:

• Simulations using RAMS:
  ➢ systematically vary traffic;

• Analytical framework:
  ➢ Assumptions;
  ➢ Spatial analysis.

• Methodology provides:
  ➢ Capacity curve;

• Framework applicable to other scenarios
A multivariate analysis of factors affecting controller workload using CAPAN/ EAM
What factors affect controller workload?

- analyse 8 ACCs peak workload;
- multivariate techniques;
- factors affecting workload
CAPAN Outputs

Main post-simulation outputs (peak hour):

- **Controller workload:**
  - By controller/ categories.
- **Flight data:**
  - Flight profiles;
  - Flight times;
  - Entry/exit;
  - Concentrations.

Q. How to analyse factors that affect controller workload?

A. Use CAPAN outputs for analysis in:

- Principal components;
- Factor analysis.
• Pool 8 ACCs:
  - High (46)/ Medium (34).
Principal Components- 1

Explains variance-covariance structure of a set of variables through a few linear combinations of these variables.

- $p$ variables reduced to $k$ principal components

Objectives:
- data reduction
- interpretation

For medium and high density ACCs:
- One dominant PC >70% of variance;
- Nature of cruising aircraft;
- Difference between high and medium.
## Principal Components Results

Major features:
- Nature of cruising aircraft
- Differences between high and medium

<table>
<thead>
<tr>
<th>ACC</th>
<th>Principal Component Number One</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH (46)</td>
<td>$0.844(Total\ Cruise\ FlightTime) + 0.371(DifferenceinFLs) + 0.310(Bi – direct.conc.)$</td>
</tr>
<tr>
<td>MEDIUM (34)</td>
<td>$0.694(Total\ Cruise\ FlightTime) + 0.478(Bi – direct.Cons.) + 0.473(DifferenceinFLs)$</td>
</tr>
</tbody>
</table>
Factor Analysis - I

Multivariate statistical techniques:

- Analysis of interrelationships amongst original variables to explain them in terms of a smaller set of underlying factors;
- Each factor a dependent variable fn. (originally observed variables).

Considerations:

- Rotation of factors to improve interpretation and simplify factor structure:
  - orthogonal - VARIMAX;
  - oblique.
Factor Analysis Results

Interpretation of 4 top rotated (VARIMAX) factor scores:

• High density ACCs:
  - cruising aircraft;
  - sector entry/exit measure;
  - climbing aircraft measure;
  - descending aircraft measure.

• Medium density ACCs:
  - trade-off between cruise and climb/descend;
  - climb/descend aircraft measure.
  - trade-offs between types of movement
Multivariate Analysis: Conclusions

Factors that affect controller workload:

- Air traffic and sector features;
- EAM simulations form 8 ACCs;
- Different factors for different ACCs;
- High density vs. Medium density ACCs:
  - similar PCs and factors;
  - cruise aircraft;
  - generic (pooled) or specific?
Airspace capacity: a cross-sectional time-series analysis using simulated controller workload data
Content

• Simulation methodology
  – features of CEATS simulation

• Panel Data Analysis
  – method
  – results

• Conclusions and future studies
The problem again

• Why just the peak hour?
  - Traffic patterns changing
  - “Peak spreading”

Workload, total number of flights and sector entries in each hour for sector C_7 of the CEATS Region during the simulation period

![Graph showing workload, total number of flights, and sector entries over time. ](image)
Other variables affecting workload

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</tr>
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Q. What are the affect of variables on workload in sectors throughout the day?

Use RAMS simulation – based methodology
RAMS Simulation: Inputs I

- **Airspace region**
  - CEATS airspace;
  - 13 ACCs;
  - 46 contiguous sectors.

- **Traffic Sample:**
  - 5400 flights in 19 hours;
  - Standard Route Structure.

- **Conflict definition:**
  - less than 2000ft vertical;
  - less than 10NM horizontal;
RAMS Simulation: Inputs II

• Planning Controller:
  - Planning Controller rules;
  - Window =>15 mins before/after sector entry/exit;
  - dynamic detection and resolution (DD&R).

• Tactical Controller:
  - Tactical Controller rules (DD&R);
  - 20 NM before/after sector entry/exit;
  - 2000 ft. below/above sector floor/ceiling;

• Sector Clipping:
  - 60 seconds in sector.

• Tasks from CEATS simulation studies (EEC).
CEATS Airspace Regions - II
Individual models:

Time Series: $W_t = \alpha + X'\beta_t + \varepsilon_{it} \Rightarrow$ for each sector

Cross Sectional: $W_i = \alpha + X'\beta_i + \varepsilon_i \Rightarrow$ for each time

Pool the data?
Method - II

Fixed Effects Time-Series Cross-Sectional Model (sector level)

\[ w_{it} = \alpha_i + x'_{it}\beta + \epsilon_{it} \]

- \( w_{it} \) = workload in sector i at time t
- \( \alpha_i \) = effects of var. peculiar sector i, constant over time
- \( X'_{it} \) = variables in sector i at time t
- \( \beta \) = coefficients
- \( \epsilon_{it} \) assumed:
  - i.i.d. over individuals i (the sectors) and time;
  - mean zero and variance \( \sigma_{\epsilon}^2 \)

Estimators from T-S C-S model are more accurate:
- Greater efficiency cf. c-s or t-s;
- Note estimated \( \alpha_i \)

Model specification - test residuals:
- Temporal correlation;
Why Panel Data?

Baltagi (1995):

- Control for individual heterogeneity.
- More informative data, more variability, less collinearity among the variables, more degrees of freedom and more efficiency.
- Study the dynamics of adjustment.
- Identify and measure effects not detectable in pure cross-sections or pure time-series data.
- Construct and test more complicated behavioural models.
- Gathered on micro units, such as individuals, or in the case of capacity analysis, ATC sectors.
Data

From RAMS Output:
• 46 Sectors;
• 20 Hours.

Q. What factors affect controller workload during the day?
• Test variables against workload:
  ➢ Aircraft and airspace geometry.

• Total Workload = (Planning+ Tactical)/ hour.

• All 20 hours/ sector – not just peak.

• Relationships to define subset of variables for analysis.
## Results I

### Fixed Effects Time-Series Cross-Sectional Model (sector level)

**Dependent variable = Total workload in hour**

<table>
<thead>
<tr>
<th>Hours of data</th>
<th>Coefficient</th>
<th>SE</th>
<th>t-statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time</strong></td>
<td>-3.46</td>
<td>1.09</td>
<td>-3.16</td>
</tr>
<tr>
<td><strong>Number of aircraft in continuous cruise profile</strong></td>
<td>-0.01</td>
<td>4.53</td>
<td>-0.00</td>
</tr>
<tr>
<td><strong>Number of aircraft in cruise-climb profile</strong></td>
<td>37.43</td>
<td>5.07</td>
<td>7.07</td>
</tr>
<tr>
<td><strong>Number of aircraft in cruise-descend profile</strong></td>
<td>12.52</td>
<td>5.68</td>
<td>2.20</td>
</tr>
<tr>
<td><strong>Number of aircraft in descend-descend profile</strong></td>
<td>-4.35</td>
<td>6.82</td>
<td>-0.64</td>
</tr>
<tr>
<td><strong>Number of aircraft in descend-climb profile</strong></td>
<td>17.33</td>
<td>11.54</td>
<td>1.50</td>
</tr>
<tr>
<td><strong>Number of aircraft in climb-climb profile</strong></td>
<td>49.37</td>
<td>8.30</td>
<td>5.94</td>
</tr>
<tr>
<td><strong>Total flight time</strong></td>
<td>0.012</td>
<td>0.004</td>
<td>3.13</td>
</tr>
<tr>
<td><strong>Average flight time</strong></td>
<td>0.053</td>
<td>0.04</td>
<td>1.30</td>
</tr>
<tr>
<td><strong>Flight level difference</strong></td>
<td>-1.05</td>
<td>0.21</td>
<td>-5.09</td>
</tr>
<tr>
<td><strong>Speed difference</strong></td>
<td>0.32</td>
<td>0.32</td>
<td>3.34</td>
</tr>
<tr>
<td><strong>Number of neighbouring sectors flight entry</strong></td>
<td>-12.87</td>
<td>5.71</td>
<td>-2.26</td>
</tr>
<tr>
<td><strong>Number of neighbouring sectors flight exit</strong></td>
<td>-13.26</td>
<td>5.45</td>
<td>-2.43</td>
</tr>
<tr>
<td><strong>Number of flights entering in cruise</strong></td>
<td>35.12</td>
<td>3.47</td>
<td>10.11</td>
</tr>
<tr>
<td><strong>Number of flights entering in climb</strong></td>
<td>12.98</td>
<td>4.19</td>
<td>3.10</td>
</tr>
<tr>
<td><strong>Number of flights entering in descend</strong></td>
<td>61.92</td>
<td>4.37</td>
<td>14.17</td>
</tr>
<tr>
<td><strong>Number of flights exiting in cruise</strong></td>
<td>7.94</td>
<td>2.79</td>
<td>2.85</td>
</tr>
<tr>
<td><strong>Number of flights exiting in climb</strong></td>
<td>0.11</td>
<td>7.15</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Number of flights exiting in descend</strong></td>
<td>9.23</td>
<td>4.25</td>
<td>2.17</td>
</tr>
</tbody>
</table>

**N = 919**

**R-Squared = 0.91**

**Rho = 0.58**
Results II

Major findings (workload in seconds, not %age):

• Flight profiles significance:
  ➢ Cruise-descend => +37 secs
  ➢ Cruise-climb => +12.5 secs
  ➢ Climb-climb => +49 secs

• 1 sec of total flight time => +0.012 secs workload;

• Average flight time NOT significant;

• Increase of 1 FL => -1 second workload;

• 1 nm/h speed diff => +0.32 secs workload;

• Neighbouring sectors entry/exit:
  ➢ ~ -12/13 secs workload;
  ➢ Spatial effects?

• Entry and exit attitudes significant:
  ➢ sector specific?;

• Time trend significant:
  ➢ Need for correction term.

N.B. Results only valid for CEATS tasks, traffic and sector patterns
Temporal Effects

Autoregressive (AR1) model:

$$\varepsilon_{it} = \rho\varepsilon_{i,t-1} + \nu_{it}$$

- $$\nu_{it}$$ i.i.d. (0, $$\sigma^2_u$$)
- $$|\rho| < 1$$

- **Test H$$^0$$: $$\rho$$=0 for panel data:**
  - Bhargava et al. (1982) modified Durbin-Watson
  - Test residuals $$\varepsilon_{it}$$

- **Modified D-W indicates serial correlation**
  - Fit AR(1) model and estimate.
## Results III

Fixed Effects Time-Series Cross-Sectional (AR1) model.

**Dependent variable = Total workload in hour**

<table>
<thead>
<tr>
<th>Hours of data</th>
<th>Hour3-Hour 22</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coefficient</td>
</tr>
<tr>
<td>Number of aircraft in continuous cruise profile</td>
<td>2.47</td>
</tr>
<tr>
<td>Number of aircraft in cruise-climb profile</td>
<td>32.90</td>
</tr>
<tr>
<td>Number of aircraft in cruise-descend profile</td>
<td>13.02</td>
</tr>
<tr>
<td>Number of aircraft in descend-descend profile</td>
<td>-5.00</td>
</tr>
<tr>
<td>Number of aircraft in descend-climb profile</td>
<td>13.25</td>
</tr>
<tr>
<td>Number of aircraft in climb-climb profile</td>
<td>36.66</td>
</tr>
<tr>
<td>Total flight time</td>
<td>0.012</td>
</tr>
<tr>
<td>Average flight time</td>
<td>0.05</td>
</tr>
<tr>
<td>Flight level difference</td>
<td>-0.81</td>
</tr>
<tr>
<td>Speed difference</td>
<td>0.25</td>
</tr>
<tr>
<td>Number of neighbouring sectors flight entry</td>
<td>-10.75</td>
</tr>
<tr>
<td>Number of neighbouring sectors flight exit</td>
<td>-7.47</td>
</tr>
<tr>
<td>Number of flights entering in cruise</td>
<td>37.14</td>
</tr>
<tr>
<td>Number of flights entering in climb</td>
<td>24.36</td>
</tr>
<tr>
<td>Number of flights entering in descend</td>
<td>67.41</td>
</tr>
<tr>
<td>Number of flights exiting in cruise</td>
<td>3.75</td>
</tr>
<tr>
<td>Number of flights exiting in climb</td>
<td>0.87</td>
</tr>
<tr>
<td>Number of flights exiting in descend</td>
<td>3.31</td>
</tr>
<tr>
<td>N</td>
<td>873</td>
</tr>
<tr>
<td>R-Squared</td>
<td>0.882</td>
</tr>
<tr>
<td>Rho_ar</td>
<td>0.28</td>
</tr>
</tbody>
</table>

\[ DW = 1.50 \]

\[ B-W = 1.57 \]
Major findings:

- Flight profiles still significant:
  - Cruise-descend => +37 secs
  - Cruise-climb => +12.5 secs
  - Climb-climb => +49 secs
- 1 sec of total flight time => +0.012 secs workload;
- Increase of 1 FL => -1 second workload;
- 1 nm/h speed diff => +0.32 secs workload;
- Neighbouring sectors entry:
  - Entry may be significant;
  - Exit NOT significant.
- Entry attitudes significant BUT not exit attitudes:
  - Similar values to entry attitudes.
- Temporal correlation statistics:
  - Modified D-W and Baltagi-Wu;
  - Indicates temporal autocorrelation.
Results V - Predictions

How good are model predictions?

Actual vs. predicted workload for all sectors through day:

- 45 deg line

Actual vs. Predicted workload for 46 sectors in CEATS region using panel data model

- Investigate major differences
Conclusions

• RAMS Simulation methodology:
  ➢ CEATS Region;
  ➢ Better geographical output;
  ➢ Hour-by-hour analysis.

• Hour-by-hour analysis more complicated than peak hour.

• Panel data analysis:
  ➢ More variables than for peak hour;
  ➢ Aircraft and sector variables;
  ➢ Correlations for time and space.

• Separate cross-section and time-series analysis:
  ➢ Check estimator efficiency;
Future study

- Panel data methodology:
  - MFF simulation;
  - Selection of variables.
Overall conclusions

Current methods of airspace have their problems.

CTS analysis of airspace capacity estimation has provided:

- A framework to estimate airspace capacity:
  - Simulation-based;
  - Analysis;
  - Capacity Curve

- Multivariate analysis of factors affecting controller workload:
  - Factors for subsequent analysis;

- Cross-sectional time-series analysis:
  - What factors affect workload in the sectors each hour?;
  - Simulation-based;
  - Methodology issues.
For more information…

Papers

**Airspace Capacity**

**Multivariate Analysis**
Websites

General
http://www.cts.cv.imperial.ac.uk

Geomatics
http://www.geomatics.cv.imperial.ac.uk