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

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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;

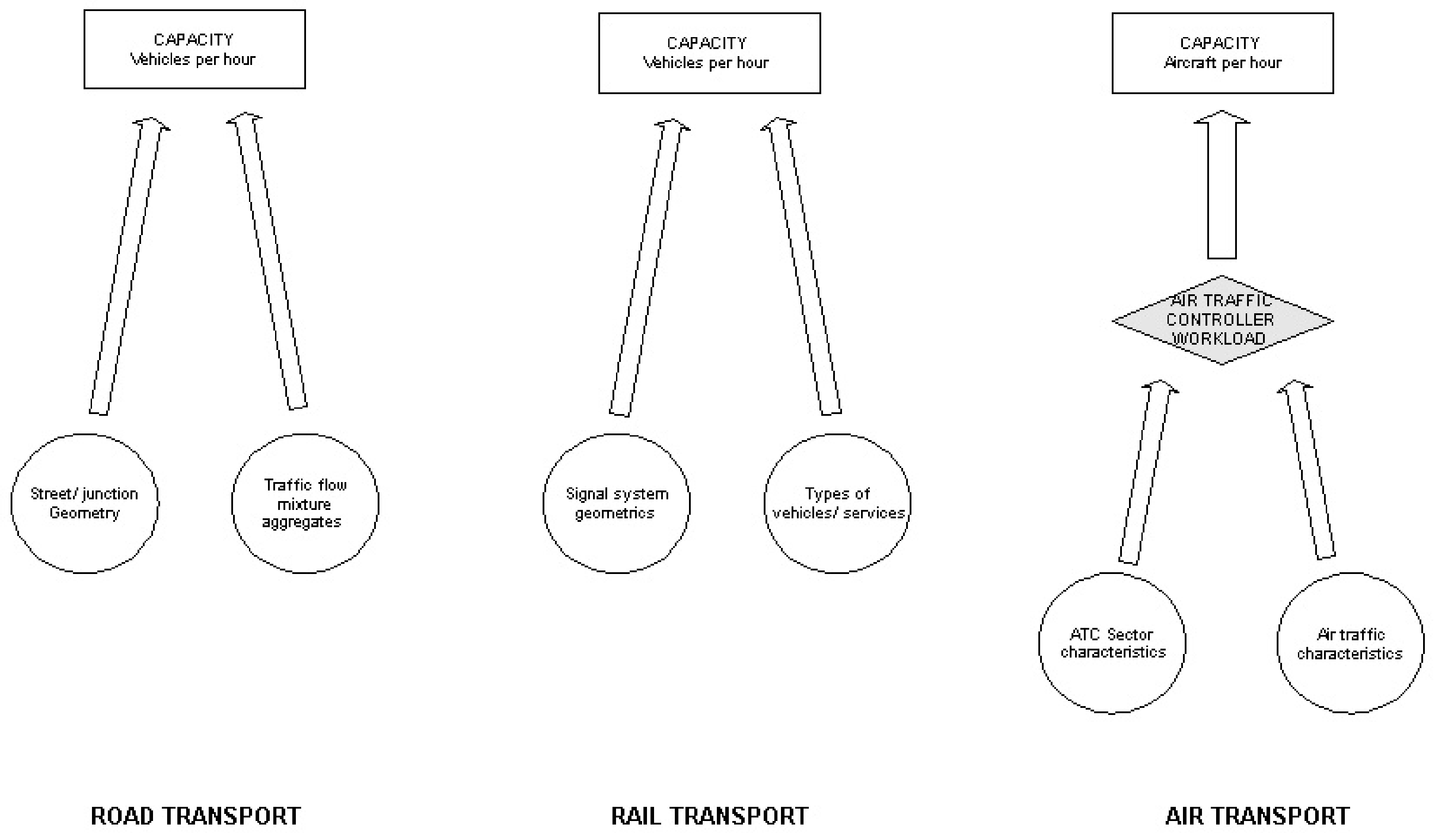
- Airspace capacity needs to be increased:
  - en-route controller workload

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

There is a need to:

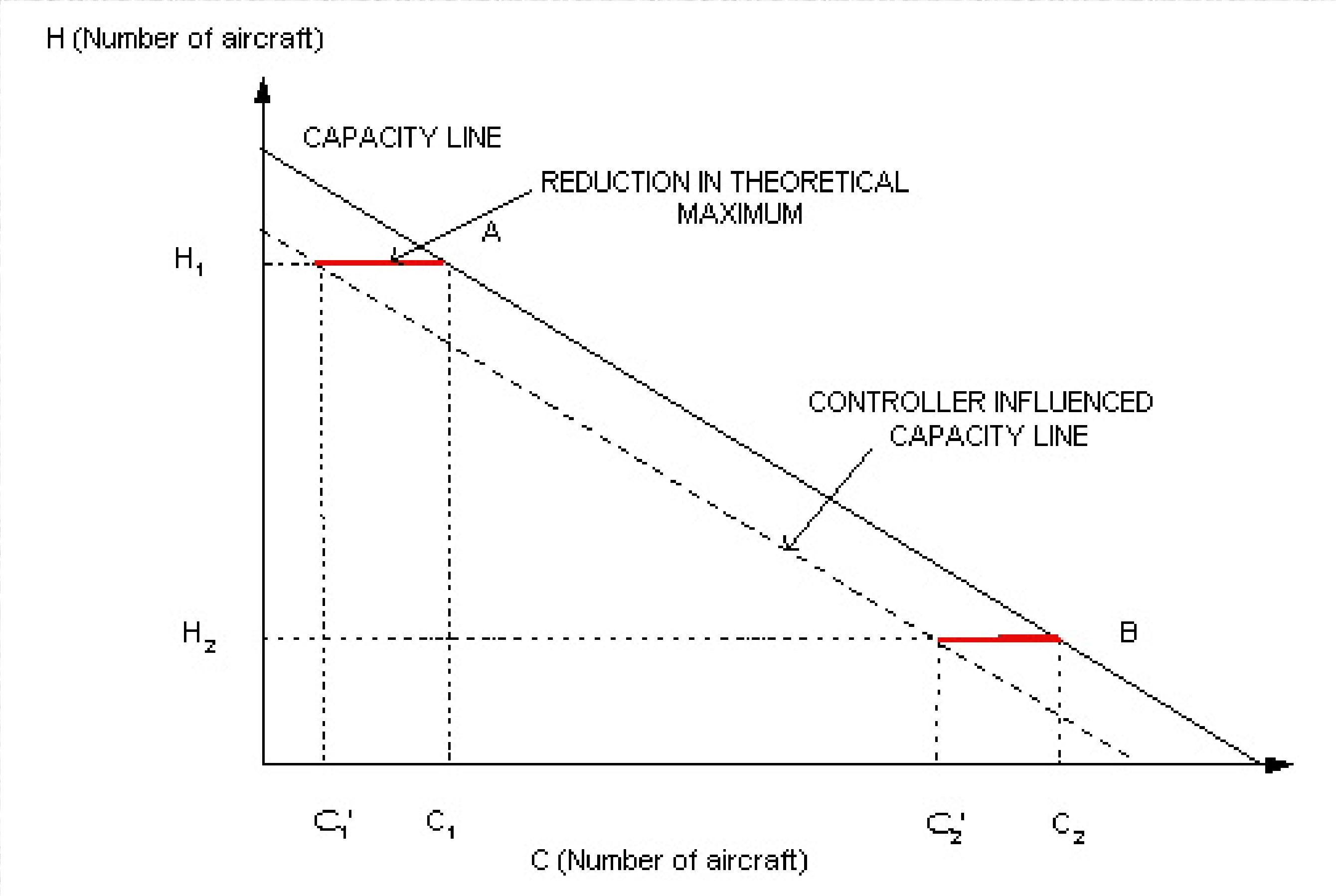
- Understand the drivers of airspace capacity;
- Develop a consistent method to estimate airspace capacity.

What makes en-route capacity different?



The controller workload problem!

Controller workload effect



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

Perceived Workload Estimates	Measured Workload Estimates
Declared Capacity	MBB Method
MACE Capacity Estimate	Task Time Methods
FAA Order 7210.46	"Schmidt" Workload Model
	Air/Ground Communications Link*
	The CARE-INTEGRA method

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

Current situation

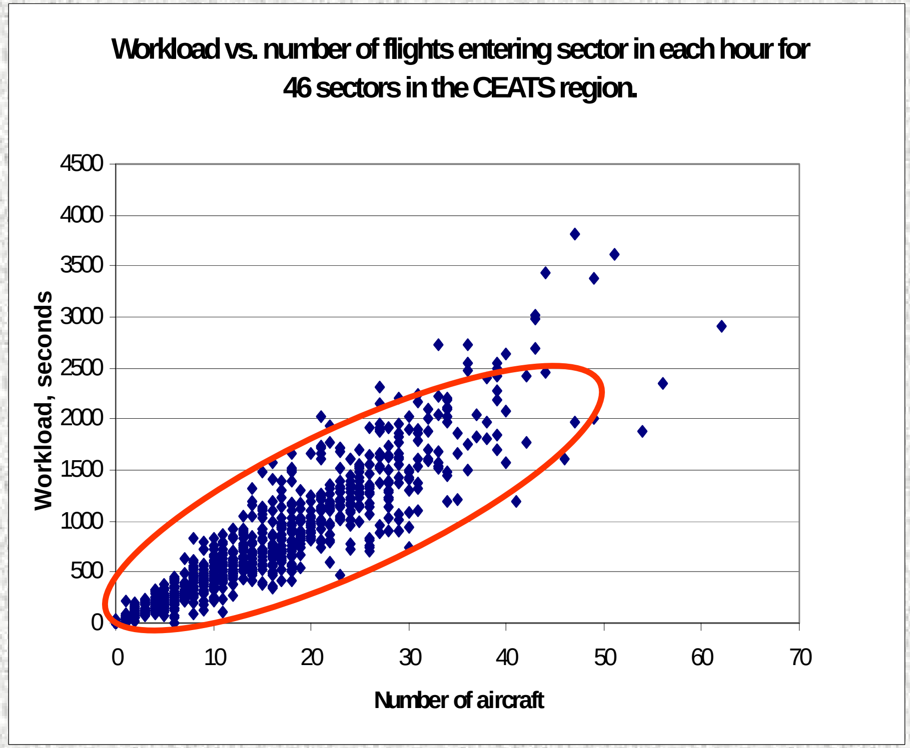
- En-route controller workload:
  - determines en-route sector capacity
- Current capacity estimation:
  - controller workload simulation;
  - workload threshold value.

Sector Capacity:

No. of aircraft entering the sector per hour, respecting the peak hour pattern, when controller workload is 70% in that hour.

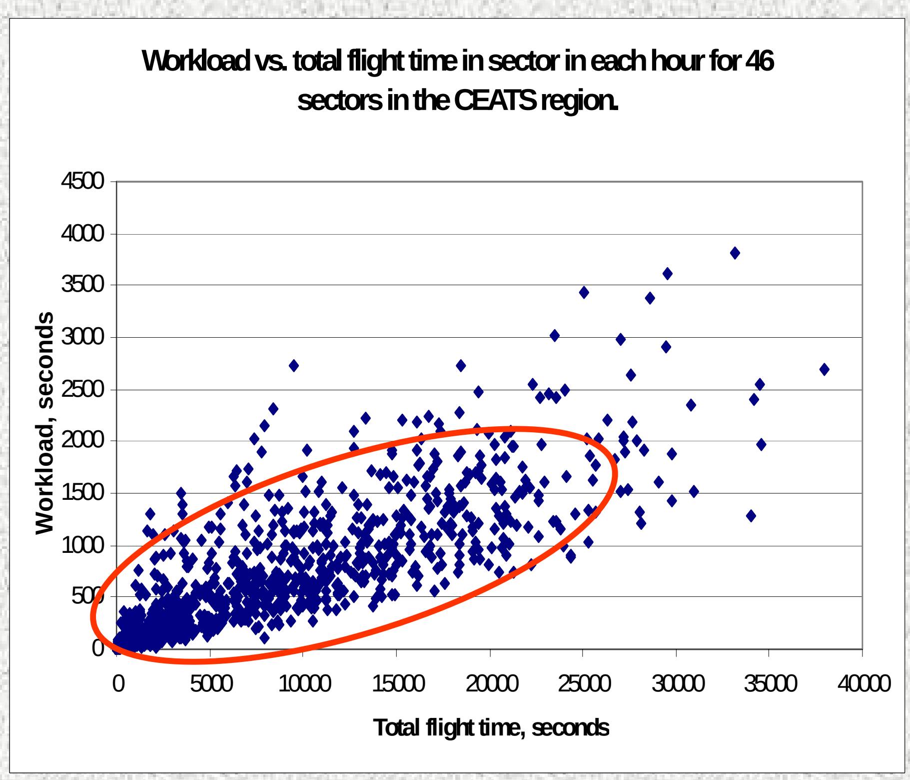
The problem - I

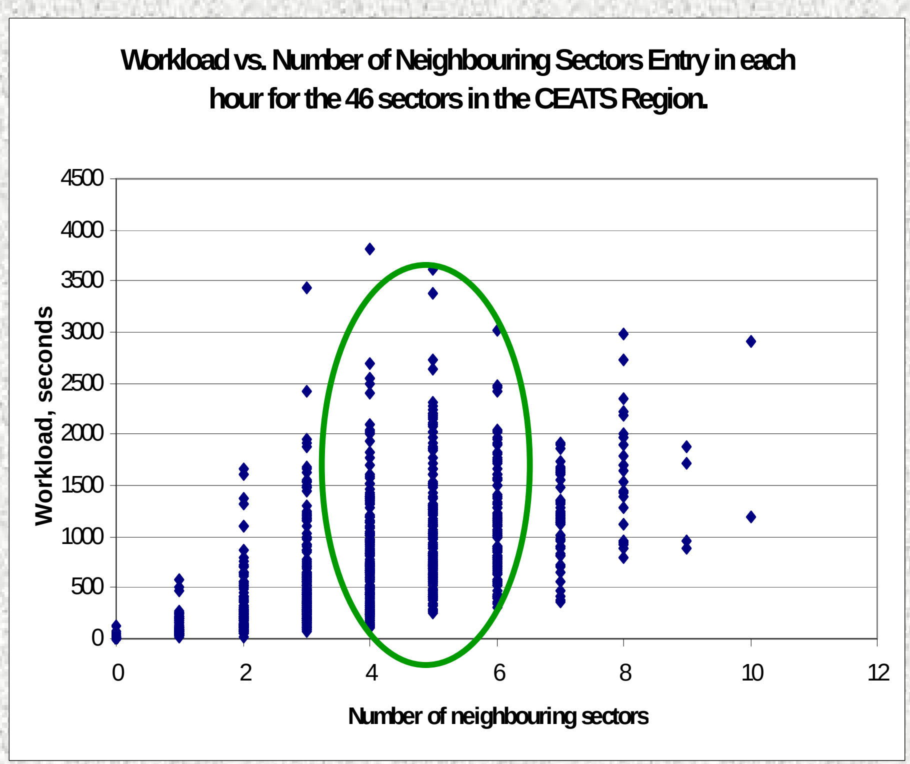
- Sector entry is the only variable:
  - ➢considerable dispersion.



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

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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

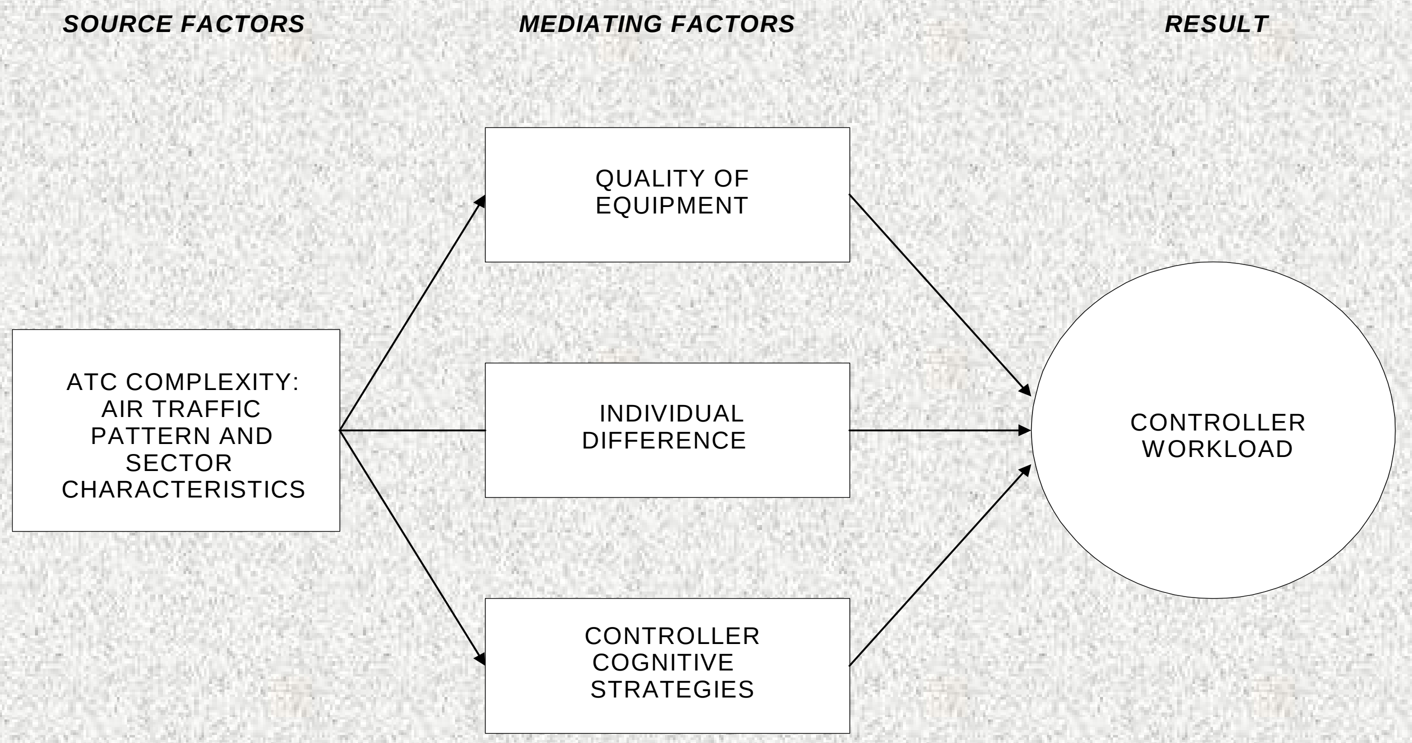
W = controller workload

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

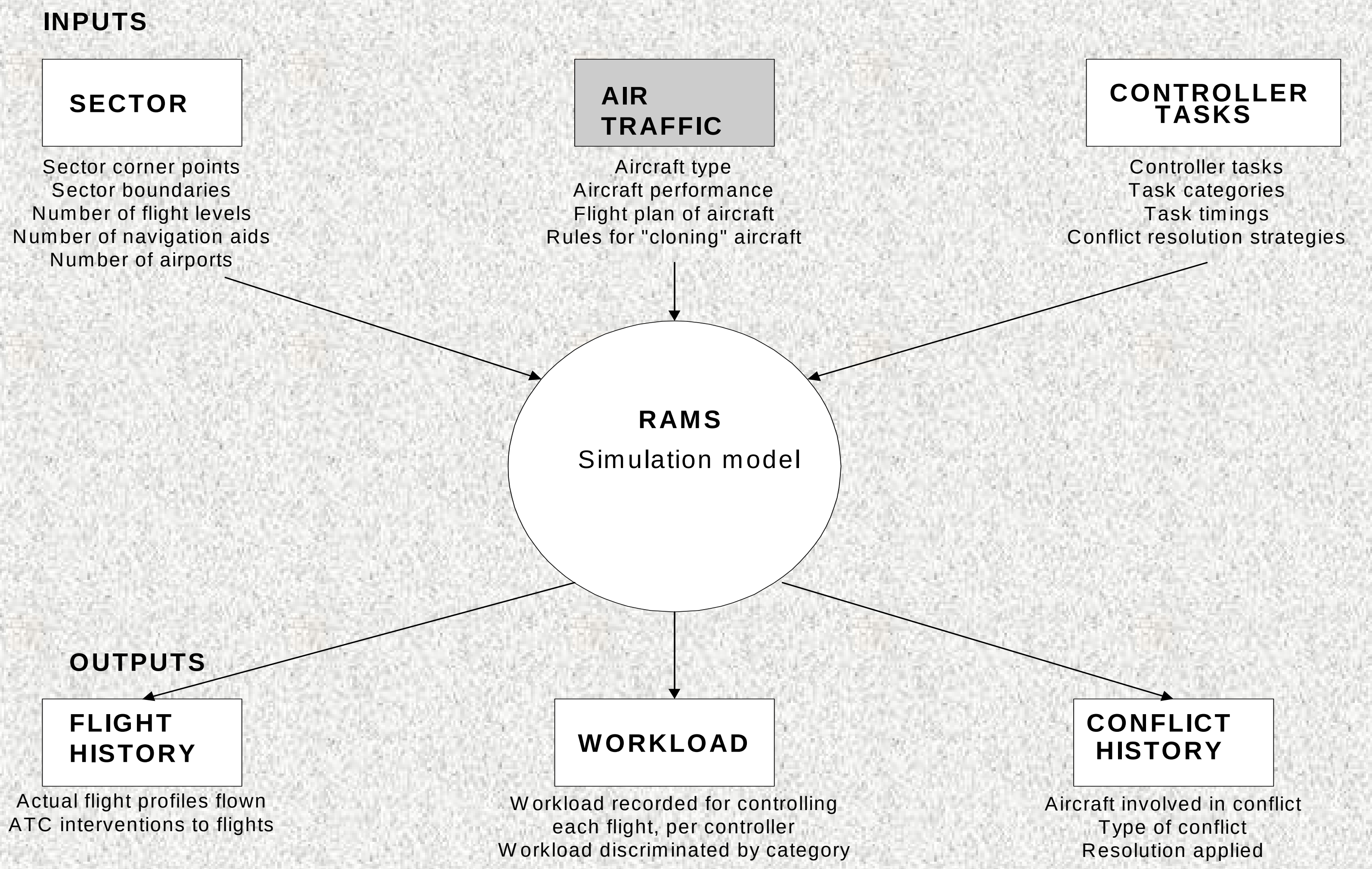
Previous research indicates:

Air Traffic Factors	**Sector Factors**
Total number of aircraft	Sector size
Peak hourly count	Sector shape
Traffic mix	Boundary location
Climbing/ descending aircraft	Number of intersection points
Aircraft speeds	Number of flight levels
Horizontal separation standards	Number of facilities
Vertical separation standards	Number of entry and exit points
Average flight duration in sector	Airway configuration
Total flight time in sector	Proportion of unidirectional routes
Average flight direction	Number of surrounding sectors

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

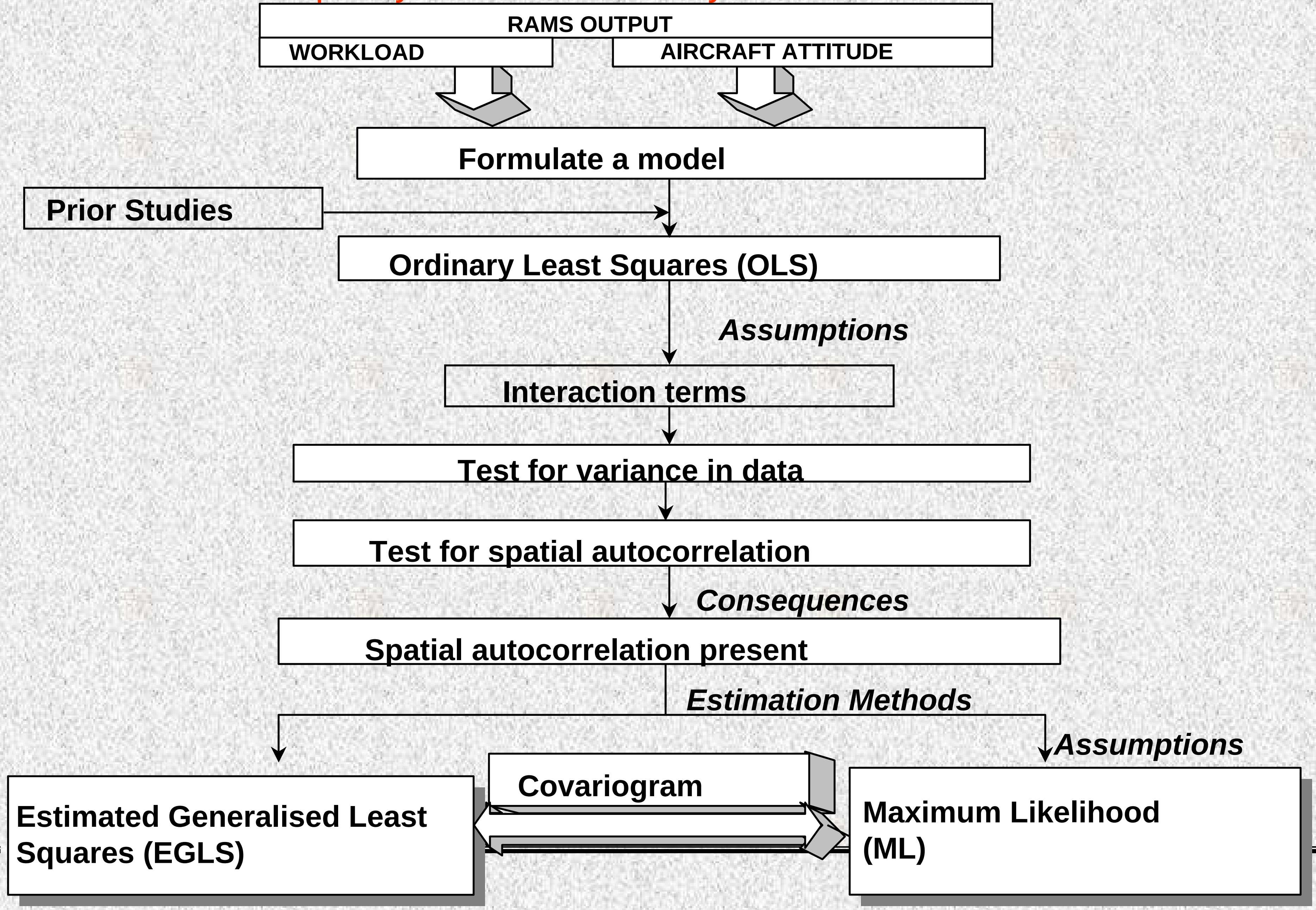


En-Route Capacity Estimation II

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



En-Route Capacity Estimation III

RAMS output:

- Workload;
- Flight history.

Functional model formulation:

- OLS;
- Test assumptions;
- Maximum Likelihood.

Spatial correlation:

- Estimation;
- Variogram.

En-Route Airspace Capacity IV

Factors that affect controller workload:

- Cruise;
- Ascend;
- $Cruise^{2}$;
- Descend x Cruise;
- Ascend x Cruise;
- Descend x Ascend.

Results

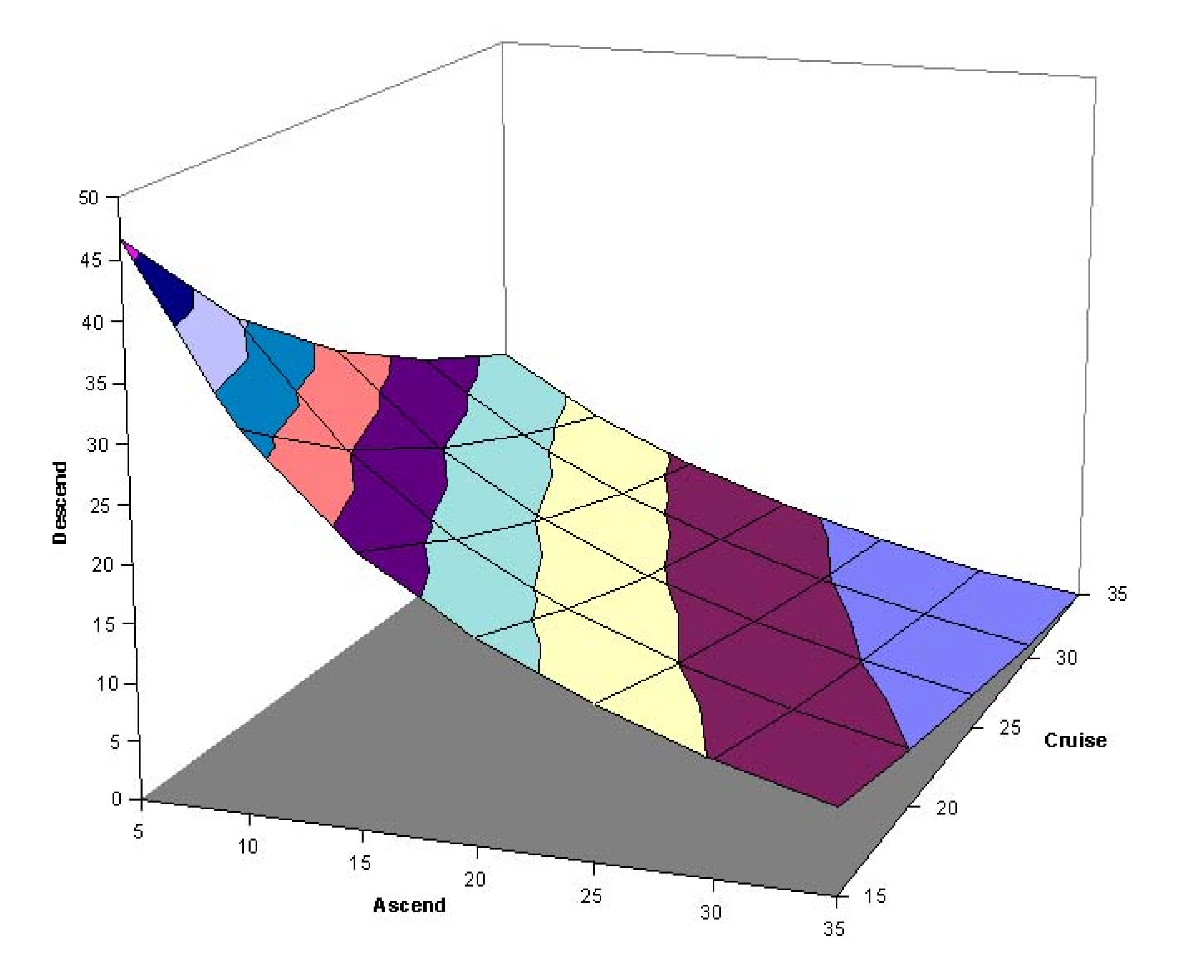
Current Demand Pattern - WLS

Variable	Parameter	SE	t
Intercept	148.54	54.73	2.71
Cruise	56.95	6.25	9.11
Ascend	46.54	8.527	5.46
$Cruise^2$	-0.57	0.069	-8.26
Descend x Cruise	4.27	0.746	5.73
Ascend x Cruise	1.67	0.634	2.62
Descend x Ascend	4.98	0.947	5.26
Adjusted R^2	0.9241		

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

Sector	DECLARED TOTAL	Declared	Diff. WLS (+)	Diff. MLE (+)
Maastricht	51	12.8	3.1	4.1
Luxembourg	41	6.2	12.8	14.3
Munich	36	12.6	20.2	21.5
Milan	41	11.1	13.4	15.5
Reims	28	1.1	27.1	29.5

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

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A multivariate analysis of factors affecting controller workload using CAPAN/ EAM

Research: EUROCONTROL DED/4

What factors affect controller workload?

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

CAPAN Outputs

Main post-simulation outputs (peak hour):

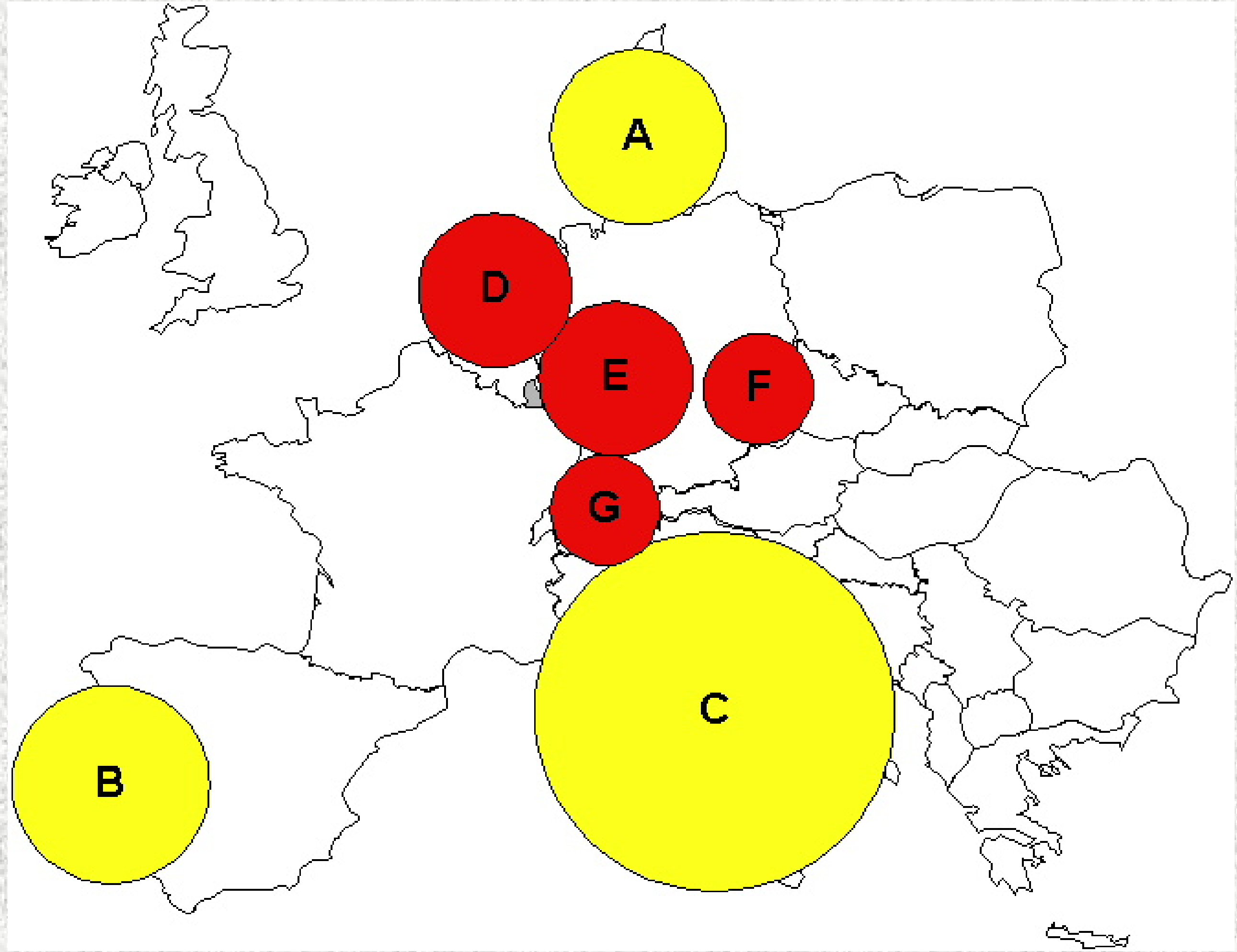
- Controller workload:
  - ➢By controller/ categories.
- Flight data:
  - ➢Flight profiles;
  - ➢Flight times;
  - ➢Entry/exit;
  - ➢Concentrations.

Q. How to analyse factors that affect controller workload?

A. Use CAPAN outputs for analysis in:

- Principal components;
- Factor analysis.

Location of ACCs



- Pool 8 ACCs:
  - High (46)/ Medium (34).

Principal Components- I

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

ACC	Principal Component Number One
HIGH (46)	$0.844(Total Cruise Flight Time) + 0.371(Difference in FLs) + 0.310(Bi - direct.conc.)$
MEDIUM (34)	$0.694(Total Cruise Flight Time) + 0.478(Bi - direct.Conc.) + 0.473(Difference in FLs)$

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?

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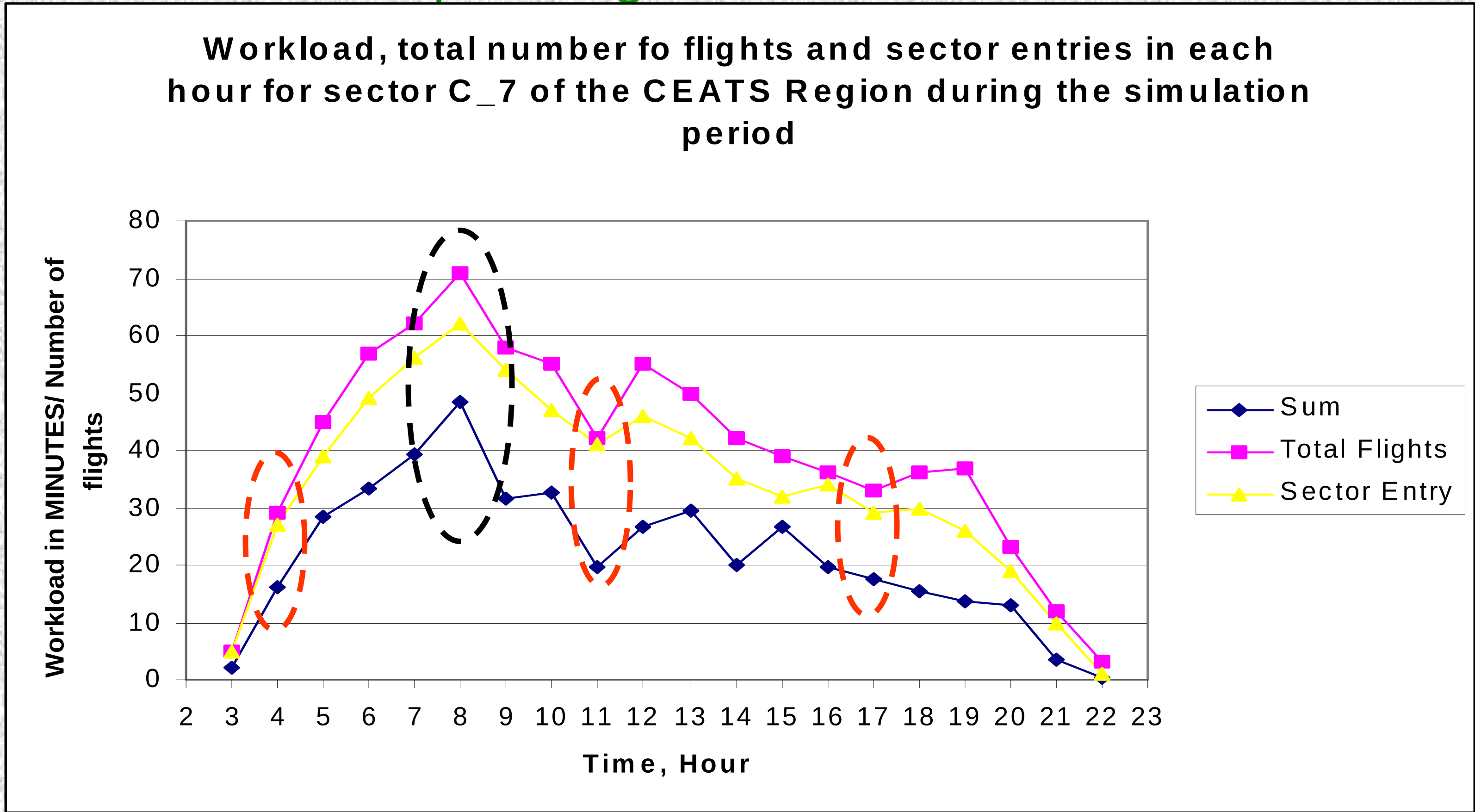
Airspace capacity: a cross-sectional time-series analysis using simulated controller workload data

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”



Other variables affecting workload

Previous research indicates:

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

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.

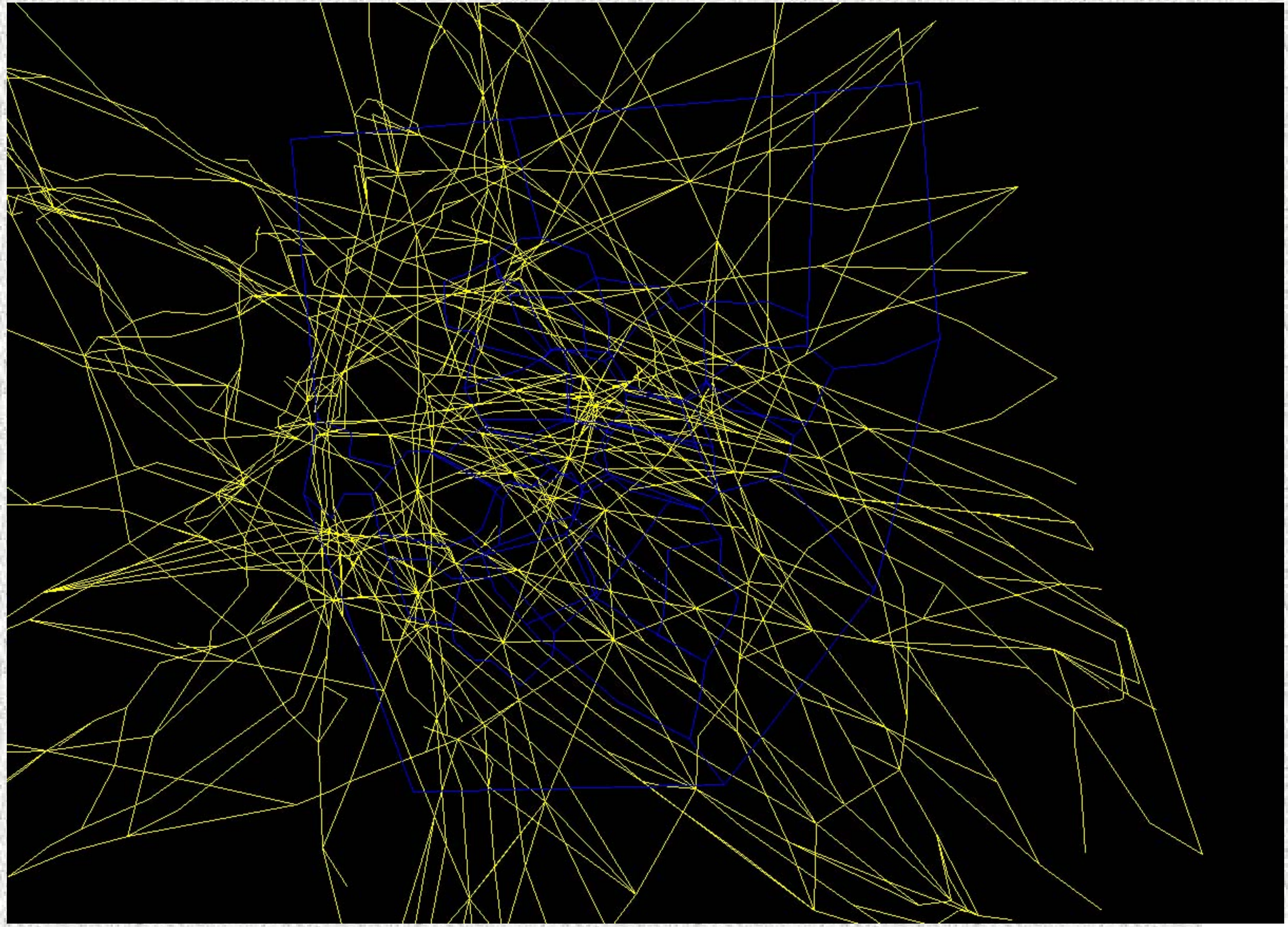
- Traffic Sample:
  - 5400 flights in 19 hours;
  - Standard Route Structure.

- Conflict definition:
  - less than 2000ft vertical;
  - less than 10NM horizontal;

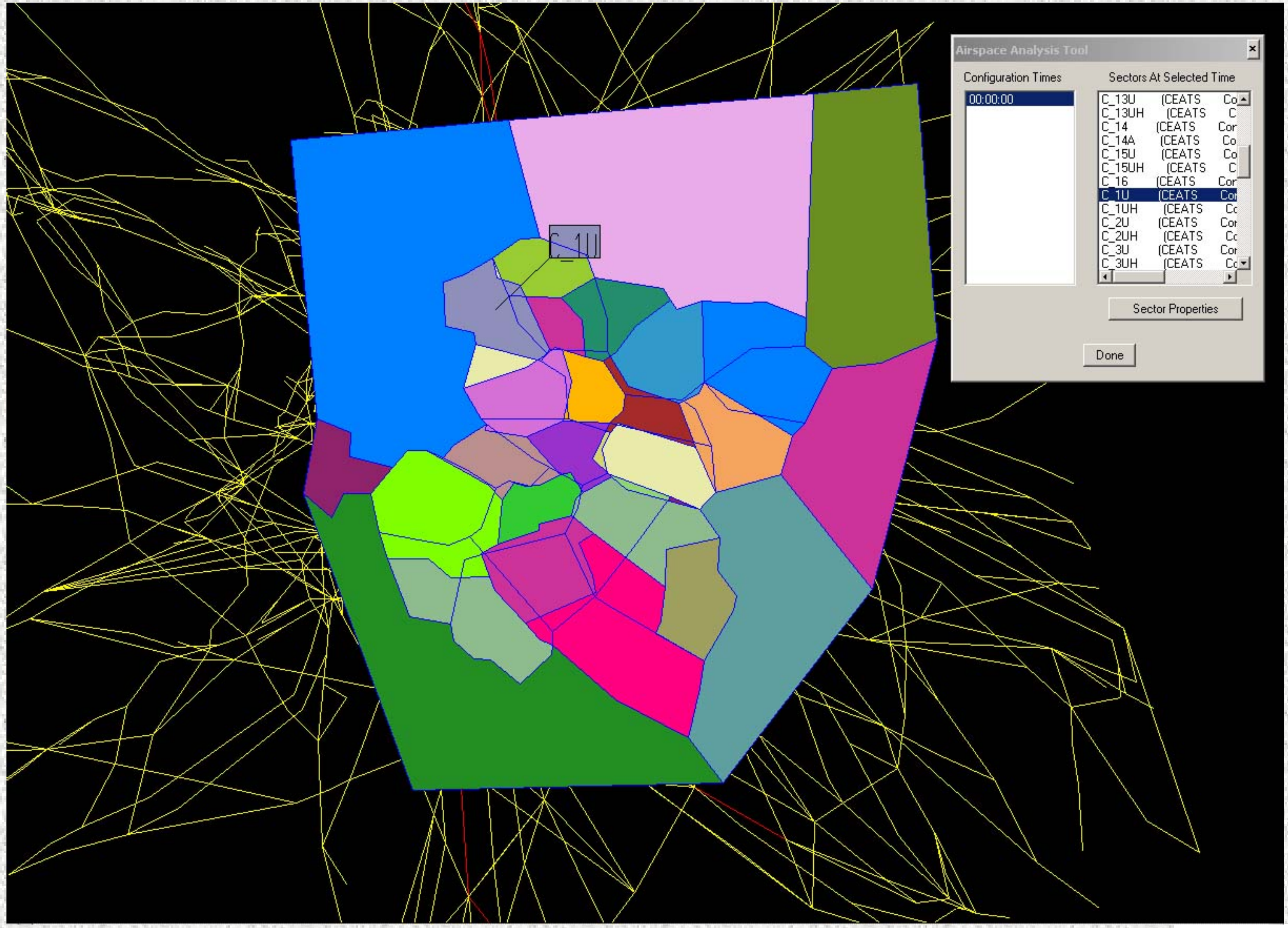
RAMS Simulation: Inputs II

- 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).

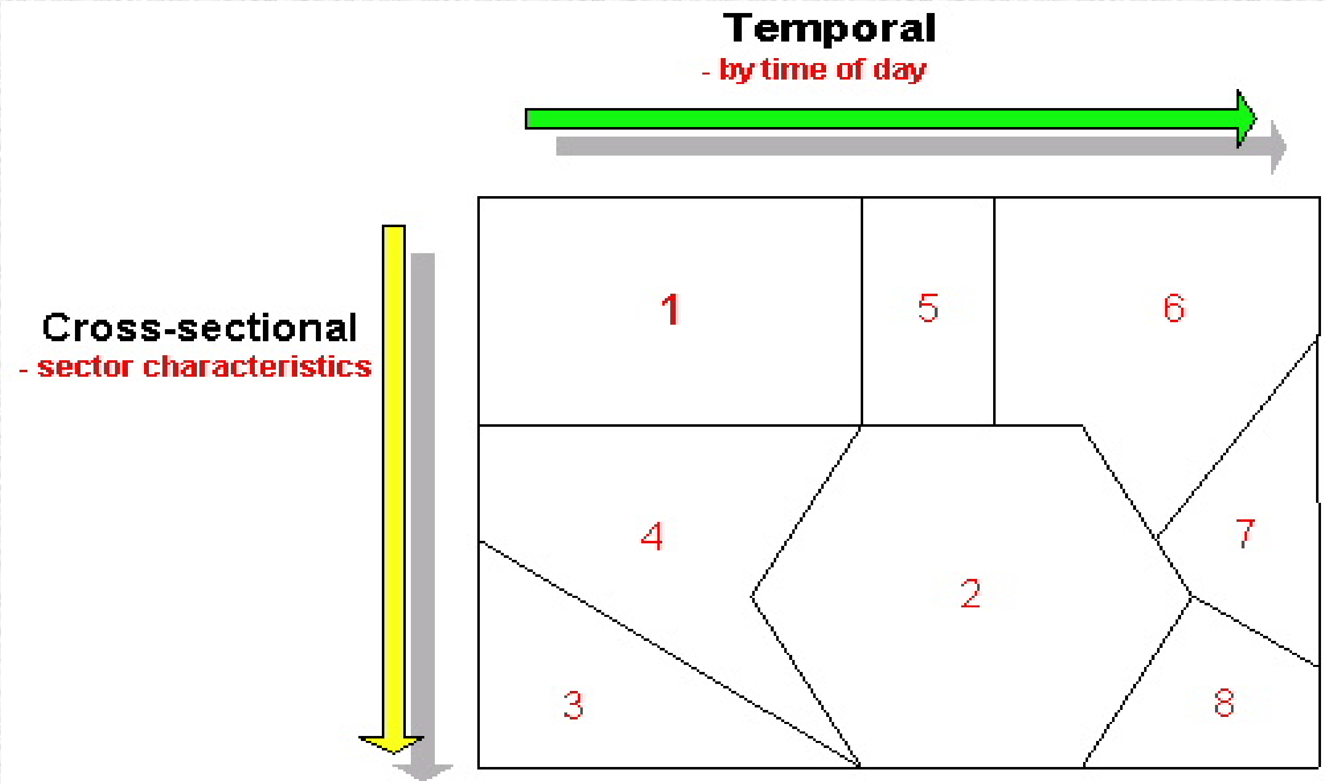
CEATS Airspace Regions - I



CEATS Airspace Regions - II



Method - I



Individual models:

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

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

Pool the data?

Method - II

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

$$w_{it} = \alpha_i + x'_{it}\beta + \varepsilon_{it}$$

w_{it} = workload in sector i at time t

α_i = effects of var. peculiar sector i, constant over time

X'_{it} = variables in sector i at time t

β = coefficients

ε_{it} assumed:

- i.i.d. over individuals *i* (the sectors) and time;
- mean zero and variance σ_ε^2

Estimators from T-S C-S model are more accurate:

- Greater efficiency cf. c-s or t-s;
- Note estimated α_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			
Hours of data	Hour 2-Hour 22		
	Coefficient	SE	t-statistic
Time	-3.46	1.09	-3.16
Number of aircraft in continuous cruise profile	-0.01	4.53	-0.00
Number of aircraft in cruise-climb profile	37.43	5.07	5.07
Number of aircraft in cruise-descend profile	12.52	5.68	2.20
Number of aircraft in descend-descend profile	-4.35	6.82	-0.64
Number of aircraft in descend-climb profile	17.33	11.54	1.50
Number of aircraft in climb-climb profile	49.37	8.30	5.94
Total flight time	0.012	0.004	3.13
Average flight time	0.053	0.04	1.30
Flight level difference	-1.05	0.21	-5.09
Speed difference	0.32	0.32	3.34
Number of neighbouring sectors flight entry	-12.87	5.71	-2.26
Number of neighbouring sectors flight exit	-13.26	5.45	-2.43
Number of flights entering in cruise	35.12	3.47	10.11
Number of flights entering in climb	12.98	4.19	3.10
Number of flights entering in descend	61.92	4.37	14.17
Number of flights exiting in cruise	7.94	2.79	2.85
Number of flights exiting in climb	0.11	7.15	0.01
Number of flights exiting in descend	9.23	4.25	2.17
N	919		
R-Squared	0.91		
Rho_ar	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:

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

- ν_{it} i.i.d. $(0, \sigma_{\upsilon}^2)$
- $|\rho|<1$

- Test H_0: $\rho=0$ for panel data:
  - Bhargava et al. (1982) modified Durbin-Watson
  - Test residuals ε_{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			
Hours of data	Hour3-Hour 22		
	Coefficient	SE	t-statistic
Number of aircraft in continuous cruise profile	2.47	4.54	0.24
Number of aircraft in cruise-climb profile	32.90	5.40	6.09
Number of aircraft in cruise-descend profile	13.02	5.60	2.32
Number of aircraft in descend-descend profile	-5.00	7.29	-0.69
Number of aircraft in descend-climb profile	13.25	11.35	1.17
Number of aircraft in climb-climb profile	36.66	8.66	4.23
Total flight time	0.012	0.004	3.07
Average flight time	0.05	0.041	1.16
Flight level difference	-0.81	0.22	-3.64
Speed difference	0.25	0.09	2.77
Number of neighbouring sectors flight entry	-10.75	5.69	-1.9
Number of neighbouring sectors flight exit	-7.47	5.43	-1.37
Number of flights entering in cruise	37.14	3.27	11.35
Number of flights entering in climb	24.36	4.91	4.96
Number of flights entering in descend	67.41	4.97	13.57
Number of flights exiting in cruise	3.75	2.79	1.34
Number of flights exiting in climb	0.87	6.89	0.13
Number of flights exiting in descend	3.31	4.20	0.79
N	873		
R-Squared	0.882		DW = 1.50
Rho_ar	0.28		B-W = 1.57

Results IV

Major findings:

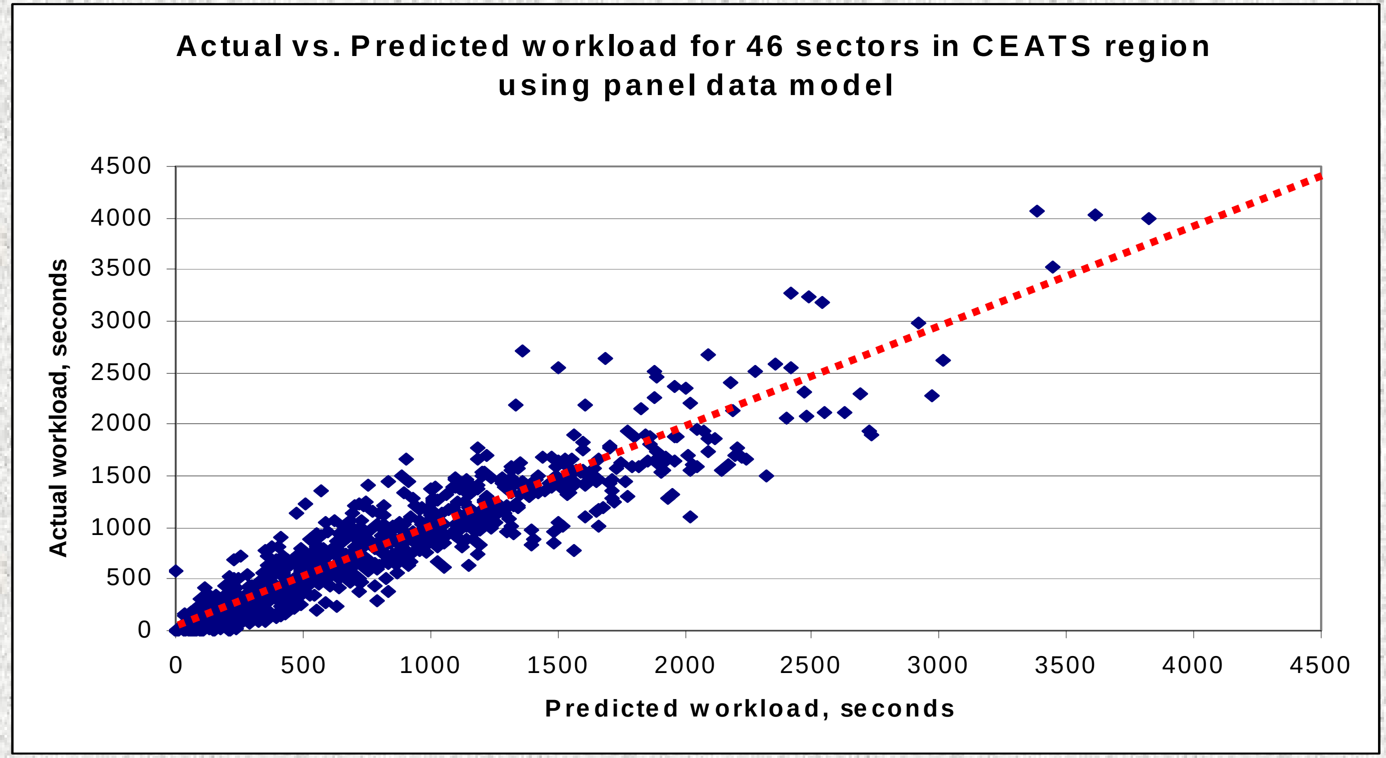
- Flight profiles still significant:
  - Cruise-descend => +37 secs
  - Cruise-climb => +12.5 secs
  - Climb-climb => +49 secs
- 1 sec of total flight time => +0.012 secs workload;
- Increase of 1 FL => -1 second workload;
- 1 nm/h speed diff => +0.32 secs workload;
- Neighbouring sectors entry:
  - 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



- Investigate major differences

Conclusions

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

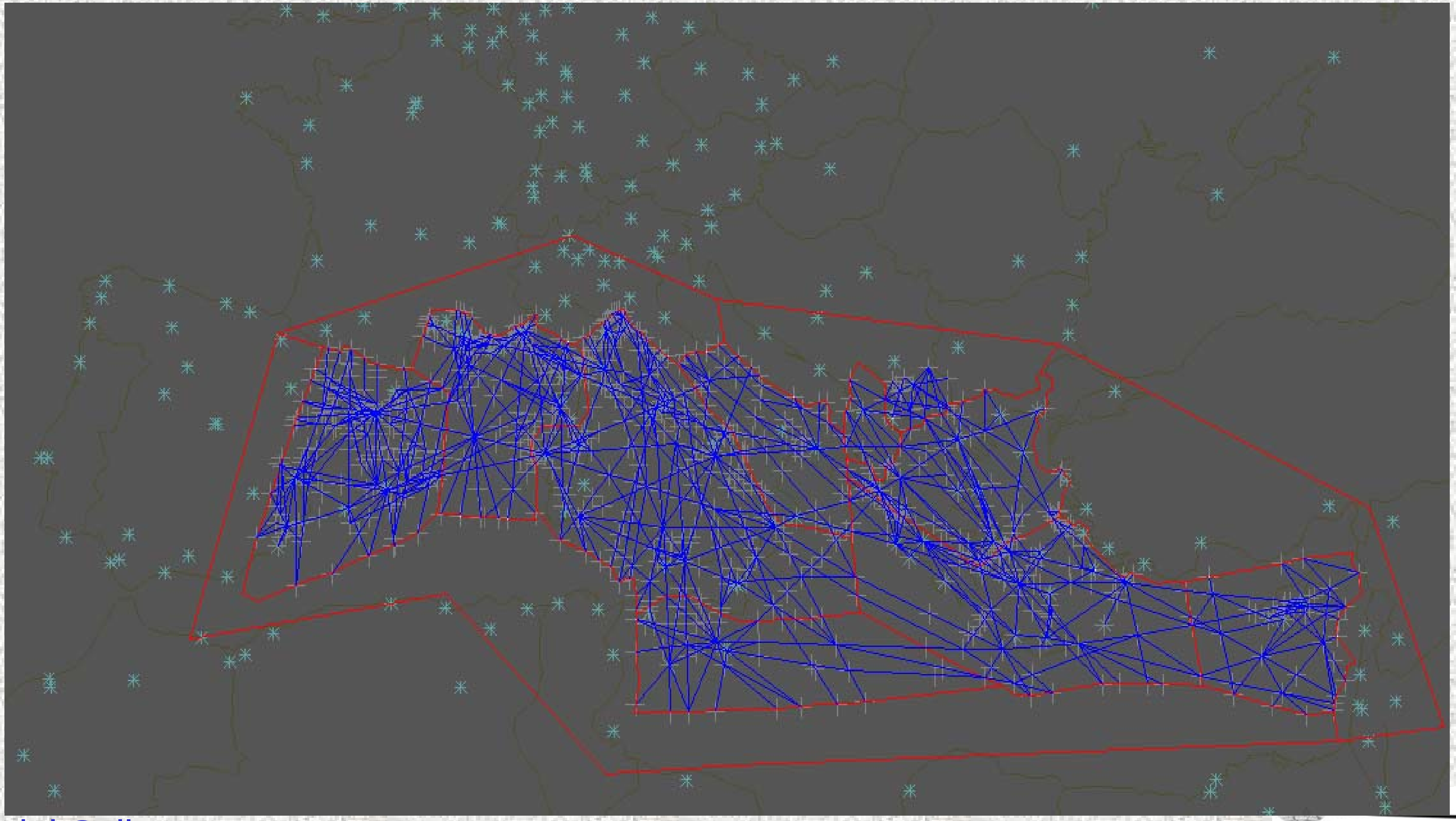
- Hour-by-hour analysis more complicated than peak hour.

- 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

Arnab Majumdar, Washington Ochieng, John Polak (2002)
Estimation of European Airspace Capacity from a Model of Controller Workload, *The Journal of Navigation* 55(2), 381-403

Multivariate Analysis

Majumdar, A. and W.Y. Ochieng (2002), The factors affecting air traffic controller workload: a multivariate analysis based upon simulation modelling of controller workload, *Transportation Research Record*, 1788 58-69*.*

Websites

General

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

Geomatics

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