# The factors affecting airspace capacity in Europe: A Framework Methodology based on Cross Sectional Time-Series Analysis using Simulated Controller Workload Data

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Air traffic in Europe is increasing at a rapid rate and traffic patterns no longer display pronounced daily peaks but instead exhibit peak spreading. Airspace capacity planning can no longer be for the peak period but must consider the whole day. En-route airspace capacity in the high density European air traffic network is determined by controller workload. Controller workload is primarily affected by the features of the air traffic and ATC sector and capacity is usually estimated using the simulation model, the Re-organized ATC Mathematical Simulator (RAMS) model of air traffic controller workload. This paper considers the air traffic and ATC sector factors that affect controller workload throughout the whole day and provides a framework using cross-sectional time-series analysis of the RAMS simulation output. Two simulation studies are presented in contrasting regions of European airspace to show the robustness of the method. Controller interviews are used to enhance the analysis. The results indicate that a sub-set of traffic and sector variables and their parameter estimates can be used to predict controller workload in any sector of the two regions simulated in any given hour.

## **KEY WORDS**

1. Air Traffic Control 2. Workload 3. Capacity 4. Cross-section time-series

## 1. INTRODUCTION

The rapid rise in European air traffic has highlighted the role of ATC and of controllers in the European aviation system. For example, in the period between 1985 and 1990, air traffic in Europe increased by 7.1% annually (EUROCONTROL, 1991). A major implication of this air traffic growth has been the rise in flight delays in Europe. For example, over a period of four years, the number of flights in Europe delayed by at least 15 minutes almost doubled (ECAC, 1998). The economic impact of delays, as well as other inefficiencies in the ATC system (e.g. non-optimal flight profiles), was calculated to cost Europe US \$5 billion annually (European Commission, 2003). The main cause of these inefficiencies has been the lack of a single, integrated ATC system throughout Europe. The European Commission has planned reform of the European air traffic control system with the aim of creating a "single European sky" (European Commission, 2003). Such moves should lead to a consolidation of air traffic management providers, and eventually reduce the number of centres controlling flights across Europe from the current 49 to perhaps four or five.

Since the late 1980s there have been various efforts led by the European Organisation for the Safety of Air Navigation (EUROCONTROL)<sup>1</sup>, to develop initiatives to tackle the en-route airspace capacity. To cope with the predicted air traffic demands, the current European Air Traffic Management Programme (EATMP) envisages a "gate-to-gate" concept, in which flights are treated as a continuum, from the first interaction with ATM until post-flight activities (EUROCONTROL, 1998). To achieve this, a broad range of procedures and technologies are considered which has the potential to change the way in which controllers work in the future ATC system of Europe.

In the European air transport network, the primary constraint at the busiest airports, e.g. London Heathrow, is the lack of runway capacity. However, for airports that are not runway constrained, the en-route airspace capacity provides a major constraint. Within the gate-to-gate concept of EATMP, any initiatives to increase current en-route airspace capacity, as well as those considering future capacity scenarios, needs a reliable definition and measure of airspace capacity. The problem here is that in the dense European air traffic environment, enroute airspace capacity depends not only upon spatial-geometrical separation criteria, but also on the workload of air traffic controllers (Arthur D. Little, 2000). There is then a need to understand controller workload and the factors that drive it. This analysis attempts to better analyse en-route airspace capacity, as opposed to other components of gate-to-gate capacity.

<sup>&</sup>lt;sup>1</sup> EUROCONTROL is the pan-European organisation established in 1960 to co-ordinate European air traffic control and air traffic management (ATC/ATM).

In addition, air traffic patterns in Europe no longer display pronounced daily peaks. There appears to be a peak spreading throughout the day making planning approaches based on daily peaks inappropriate. Instead, to improve airspace capacity planning, it is important to understand the factors that affect controller workload, and their impact throughout the day.

This paper provides a method to assess the impact of these factors on controller workload throughout the day, known as cross-sectional time series analysis. This analysis should help to develop a reliable functional relationship between air traffic controller workload and the various factors that affect it. The research presented in this paper uses a realistic simulation model of air traffic controller's workload to do this.

Section 2 of the paper provides a brief explanation of the European airspace capacity estimation problem, emphasising the critical role of the air traffic controller workload. Section 3 examines the factors that affect controller workload and airspace capacity. Section 4 discusses the issues to be considered in a simulation exercise involving air traffic controller workload, whilst Section 5 outlines the Re-organized ATC Mathematical Simulator (RAMS) (EUROCONTROL; 1996a, 1996b) to be used in a series of simulation experiments. The methodology of cross-sectional time series analysis, also known as panel data analysis, is discussed in Section 6. Sections 7 and 8 outline the main features of two contrasting simulation scenarios that are analysed by cross-sectional time-series to show the robustness of the method. A particular feature of the analysis described in Section 8 is the use of controller interviews to enhance the cross-sectional time-series analysis. The paper is concluded in Section 9.

## 2. EUROPEAN AIRSPACE CAPACITY ESTIMATION.

Experience in Europe suggests that en-route airspace capacity e.g. that of an ATC sector, is determined by air traffic controller workload i.e. the mental and physical work done by the controller to control traffic (Majumdar and Polak, 2001). This is in addition to spatial-geometric and temporal criteria based upon the performance characteristics of the aircraft in the sector (EUROCONTROL, 1991).

The capacity of an ATC sector can therefore be defined as the *maximum number of aircraft that are controlled in a particular ATC sector in a specified period*, while still permitting an *acceptable level of controller workload*. Such a definition requires three criteria to be determined:

• the definition controller workload;

- a method for measuring controller workload; and
- quantification of an acceptable level of controller workload, i.e. the threshold value at full capacity.

Controller workload is a confusing term with a multitude of definitions, models and measures in the literature (Jorna, 1991). The practice in en-route airspace capacity estimation in Europe is to use simulation modelling of controller workload where the workload is given by tasktime definitions obtained from a detailed non-intrusive objective record of the controller's actions by an independent observer (EUROCONTROL, 1996). Such records are supported by controller verification of the tasks and their timings, especially for those tasks that involve a significant mental component. Based upon these task-time definitions, threshold controller loadings are defined for the number of minutes/ hour that controllers are occupied in their tasks as recorded by the models, e.g. RAMS, described in more detail in Section 5. (EUROCONTROL 1999). The capacity of an en-route ATC sector, is then defined as the maximum number of aircraft controlled in a sector per hour given this threshold controller loading.

## **3** AIRSPACE CAPACITY DRIVERS

Research indicates that the workload experienced by air traffic controllers, however it is defined and measured, is affected by the complex interaction of (Mogford et. al 1995):

- a) the situation in the airspace i.e. by features of both the air traffic and the sector;
- b) the state of the equipment i.e. by the design, reliability and accuracy of equipment in the control room and in the aircraft; and

c) the state of the controller, e.g. the controller's age, experience, decision making strategies. These parameters can be thought of as the drivers of controller workload, and consequently of en-route airspace capacity, i.e. *airspace capacity drivers*. Thus the effect of these parameters on controller workload must be understood if realistic and successful strategies for increasing airspace capacity are to be implemented. Figure 1, based on Mogford et al. (1995), outlines how these capacity drivers affect controller workload with the primary factor affecting workload being the situation in the airspace. This is determined by:

- physical aspects of the sector, e.g. size or airway configuration; and
- factors relating to the movement of air traffic through the airspace, e.g. the number of climbing and descending flights; and
- a combination of the above factors which cover both sector and traffic issues, e.g. required procedures and functions.

This interaction between sector and traffic features can be thought of as ATC complexity, and it is this that generates workload for the controller.



FIGURE 1: FACTORS AFFECTING CONTROLLER WORKLOAD Source : Mogford et al. (1995), page 5

There are various reviews of the effect of these drivers on controller workload (Majumdar and Ochieng, 2002, Hilburn 2004). From these sources a list of factors that impact upon controller workload can be derived, e.g. Table 1. There have also been various recent attempts to quantify the effect of ATC complexity on controller workload, e.g. the "dynamic density" concept of NASA (Laudeman et al., 1998).

Table 1. List of air traffic and sector factors that can affect ATC complexity and controller workload.

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 flight levels
Aircraft speeds	Number of facilities
Horizontal separation standards	Number of entry and exit points
Vertical separation standards	Airway configuration
Minimum distance between aircraft	Proportion of unidirectional routes
Aircraft flight direction	Number of facilities.
Predicted closest conflict distance	Winds
Flow entropy	
Number and type of conflicts	
Aircraft Clustering	
Amount of time aircraft is controlled	
Changes in altitude/ heading/ speed	

The crucial factor that arises from such research is that more than just a single air traffic variable affects workload and, given a threshold workload value, airspace capacity. Therefore

estimating airspace capacity based upon the relationship between controller workload and single air traffic variable, i.e. the number of aircraft entering the sector in given period (outlined in EUROCONTROL, 1996), is not totally adequate.

Previous studies by Majumdar and Polak (2001), and Majumdar and Ochieng (2002) considered just the peak workload hour of the simulation. Subsequently, Majumdar et al. (2004) went further by considering the drivers that affect controller workload in a region of European airspace throughout the day. This should help ATC/ATM planners and managers in their task by enabling them to estimate accurately the controller workload throughout the day based upon a particular set of drivers in any given sector at any given time of day. Their initial results indicated promise in the method.

The following section outlines the considerations of this simulation modelling approach.

## 4. SIMULATION MODELLING OF EUROPEAN EN-ROUTE AIRSPACE

Wickens et al. (1997), Magill (1998) and Majumdar and Polak (2001) note the importance of and advantages in the use of simulation modelling in ATC capacity estimation. Three questions need to be answered in order to make effective use of simulation modelling:

- How will the work done by the ATC system be characterised by the simulation model?
- How well does the simulation model used represent the reality of the ATC system?
- what rules for the elements of the simulation model need to be encompassed for the simulation scenarios in order to generate the appropriate output for analysis?

The task time thresholds mentioned in Section 2 for various air traffic controller workload simulation models deals with the first of these questions. These thresholds have been validated by several real-time studies and the experience gained from previous simulation results, as well as from field studies (e.g. EUROCONTROL 1999).

As a priority, it is important to ensure that the simulation model chosen realistically reflects the "real world" airspace environment under consideration. Furthermore, it should be calibrated to give reasonable estimates of workload. The following section outlines the features of the simulation model used this study to encompass these questions.

## 5. THE REORGANIZED ATC MATHEMATICAL SIMULATOR (RAMS)

The Re-Organized ATC mathematical Simulator (RAMS) (EUROCONTROL 1995, chosen for the research presented in this paper, is a discrete-event simulation model of air traffic controller workload. Whilst there are other controller workload simulation models, RAMS together with its predecessor the European Airspace Model, has been used widely for 25 years in Europe for airspace planning. The model has been verified by controllers (EUROCONTROL 1999). In the model, each control area is associated to a sector, which is a 3-dimensional volume of airspace as defined in the real situation. Each sector has two control elements (planning and tactical) associated with it (Figure 2). The control areas maintain information regarding the flights wishing to penetrate them, and have associated separation minima and conflict resolution rules that need to be applied for each of the two RAMS control elements. This reflects the teamwork aspect of control seen in practice. Also, the simulation engine permits the input of rules for these controllers that mimics reality. The task base in RAMS contains a total of 109 tasks undertaken by controllers, together with their timings and position, grouped into five major areas. The use of RAMS for this study means that the EUROCONTROL definition of a control team (Tactical and Planning) at capacity being 42 minutes/hour loading has been adopted.

Figure 2. The control elements in RAMS.





There are a range of methodological issues to be addressed to ensure the veracity of the results of a simulation model, see Majumdar and Polak (2001). Figure 3 shows the major inputs and outputs of the RAMS model. Crucial to the simulation are the controller tasks represented by the set of controller tasks and their timings as contained in the controller task input files. The choice of an appropriate set and its implications are of the utmost importance in both undertaking and understanding the simulation results.



Figure 3. The inputs and outputs into the RAMS model.

The following section outlines the use of the simulation outputs of RAMS in the panel data methodology.

## 6. PANEL DATA METHODOLOGY

The output data from RAMS of interest in this analysis are those for the workload and the flight history, Figure 3. Thus, for a given traffic demand pattern in the airspace simulation area, an attempt is made to fit an analytical model to the RAMS output data to formulate a relationship between controller workload and the variables that affect it (i.e. various flight and sector data, throughout the day). There is a need to consider the factors affecting controller workload not just in the peak hour, but also in successive time periods, as well as account for the heterogeneous nature of the sectors in the simulation area.

A technique used in econometrics that accounts for both heterogeneity and time is the crosssectional time-series, or "panel data" analysis (Baltagi, 1995). Panel data in econometrics traditionally refers to the pooling of observations on a cross-section of e.g. households, countries, over several time periods. This can be achieved by surveying a number of households or individuals and following them over time. In the case of airspace capacity analysis, panel data refers to the pooling of observations on a cross-section of ATC sectors over several periods of time, e.g. one hour intervals.

The major benefits of using panel data are outlined in (Baltagi 1995):

- Controlling for individual heterogeneity. Panel data analysis assumes that individuals, countries and in the case of airspace research, ATC sectors, are heterogeneous. Timeseries and cross-section studies, which do not control for this heterogeneity, run the risk of obtaining biased results.
- Provision of more informative data, more variability, less collinearity among the variables, more degrees of freedom and more efficiency.
- The data are better suited to study the dynamics of adjustment.
- The data are better suited to the identification and measurement of effects that are simply not detectable in pure cross-sections or pure time-series data.
- The data are usually gathered on micro units, such as individuals, or in the case of capacity analysis, ATC sectors. Many variables can be more accurately measured at a micro level, and biases resulting from aggregation over firms or individuals are eliminated.

The RAMS simulation output data can be analyzed using a fixed effects time-series crosssectional model. The data is at the sector-level and the inclusion of fixed effects allows for the control of other factors that might have influenced controller workload for which data is unobservable (Verbeek, 2001). For example, this could include specific ATC procedures that may have been implemented in some ATC sectors. These methods are simple to implement and consist of ordinary least squares (OLS) regression with a dummy variable included for each cross-section, in this case the sector. The OLS estimators have optimal properties when the Gauss-Markov conditions are met. This means that the estimators are unbiased, linear and have the minimum variance of any class of linear, unbiased estimators, i.e. they are "best". For the standard fixed effects model:

$$y_{it} = \alpha_i + x'_{it}\beta + \varepsilon_{it}$$
(2)

the error term  $\varepsilon_{it}$  is assumed to be independent and identically distributed over individuals *i* (i.e. the ATC sectors) and time, with zero mean and variance  $\sigma_{\varepsilon}^2$  (Verbeek, 2001). The workload in sector *i* in time *t* is  $y_{it}$  and  $\beta$  represents the coefficients.

 $x_{it}$  is a *K*-dimensional vector of explanatory variables, not including a constant. This means that the effects of change in *x* are the same for all units and all periods, but that the average

level for unit *i* may be different from that unit *j*.  $\alpha_i$  thus capture the effects of those variables that are peculiar to the *i*-th individual and that are constant over time.  $\alpha_i$  are treated as *N* fixed unknown parameters.

After fitting a model, there is then a need for diagnostic testing to ensure the appropriate model has been selected. In particular there is a need to consider the potential temporal autocorrelation (or serial correlation) in the data undertaking the Bhargava et al.(1982) test and then correcting with a first-order autoregressive process AR(1).

Based upon the above, a panel data (i.e. cross-sectional time-series) analysis on the basis of the output of a RAMS simulation seems an appropriate method for estimating the functional relationship between controller workload and its drivers i.e. a number of possible explanatory variables,  $x_{it}$ , outlined in Table 2.

Table 2. List of independent va	iables obtained from the RAMS output.
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Air Traffic Factors	Airspace geometry Factors
Total number of aircraft	Sector shape
Number of aircraft in continuous cruise profile	Number of flight levels available
Number of aircraft in cruise-descend profile	Number of navaids
Number of aircraft in cruise-climb profile	Number of airports
Number of aircraft in climb-climb profile	Number of neighbouring sectors from which aircraft enter
Number of aircraft in descend-climb profile	Number of neighbouring sectors to which aircraft exit
Number of aircraft in descend-descend profile	
Number of aircraft entering sector in cruise	
Number of aircraft entering sector in climb	
Number of aircraft entering sector in descend	
Number of aircraft exiting sector in cruise	
Number of aircraft exiting sector in climb	
Number of aircraft exiting sector in descend	
Average flight duration in sector	
Total flight time in sector	
Aircraft speeds	

The strategy used to attempt to formulate a functional relationship between controller workload and appropriate air traffic and sector variables is outlined in Figure 4.



Figure 4. The modelling strategy for cross-sectional time-series analysis

## 7. THE CEATS SIMULATION SCENARIO.

A simulation study conducted for the Central European Air Traffic Services (CEATS) Upper Area Control Centre, is outlined in Majumdar et al. (2004). The CEATS region comprises of en-route airspace of Austria, Bosnia and Herzegovina, Croatia, Czech Republic, Hungary, Italy, Slovak Republic and Slovenia. The airspace of the CEATS region consists of 46 contiguous sectors with thirteen Area Control Centres (ACCs). This gave a sufficiently large number of heterogeneous ATS sectors for subsequent analysis. The traffic sample used consisted of 5400 flights in twenty hours, following a standard route structure.

Table 3 indicates the major results, and these are explained as follows. Three flight profile variables were significant statistically significant at the 5% level of significance:

- The number of aircraft with cruise-climb profile. Therefore, each aircraft with a cruiseclimb increases controller workload by 37 seconds across any sector of the CEATS region in any hour;
- The number of aircraft with cruise-descend profile. Each aircraft with cruise-descend profile increases controller workload by 12.5 seconds across any sector of the CEATS region in any hour;
- The number of aircraft with climb-climb profiles. Each aircraft with a climb-climb profile increases controller workload by 49 seconds across any sector of the CEATS region in any hour;

The total flight time was found to be significant at the 5% level, with every second of the total flight time variable increases controller workload by 0.012 seconds.

The variable for the difference in flight levels used is significant and negative, indicating that for every difference of one flight level, controller workload decreases by one second. This implies that the more flight levels there are in a sector, the less the workload associated with factors such as conflict resolution. Presumably more flight levels give controllers more options to avoid conflicts in a sector.

The speed difference variable is significant and indicates that for every 1 nm/h speed difference between the fastest and slowest aircraft in the sector, controller workload increases by 0.32 seconds. Therefore, the greater the speed homogeneity in a sector, the more preferable it is for controller workload, i.e. less workload.

The variables for the number of neighbouring sectors from which aircraft enter a sector, and exit from a sector were found to be significant and negative. Therefore, for every neighbouring sector into which aircraft could enter or from which they could exit, controller workload decreased by 12 to 13 seconds. A possible explanation for this is that whilst more sectors indicate increased coordination workload, this effect is counteracted by the reduced workload for conflict detection and resolution in any sector, though sector size effects need to be considered in this case. In addition, the neighbouring sectors could indicate spatial effects in the data not adequately captured by the variables present in this analysis.

Barring the number of aircraft exiting a sector in climb, all the other variables relating to flight phases for aircraft entry and exit into a sector are significant and positive in sign and value. This indicates that these variables combining both sector entry/ exit and flight phase increase controller workload, the actual amount varying between 61 seconds for flights entering sector in descend and 9 seconds for flights exiting sector in descend.

The predictive capabilities of this technique were strong. When the data is considered for all the 46 sectors for 20 hours, a plot of actual workload recorded against the estimated workload gives an indicator of the measure of accuracy of the model. Figure 5 shows this plot, along with a 45 degrees line. This line indicates how closely the model predicts the actual workload, since if the "actual" and predicted workloads were always equal, all points in this graph would lie along this line. This figure shows that the model estimates reasonably well the actual workload, though anomalies at high workloads should be investigated. Therefore it seems that a subset of about ten significant variables, with their estimated parameter values,

can adequately predict the simulated workload obtained using RAMS in any given sector in the CEATS region in any given hour. However, given the bespoke nature of ATC in different airspace regions of Europe, there may be a need to consider other variables. Anomalies in the results could be due to possible model misspecification, requiring the need to include quadratic variables to account for interactions.

Dependent variable = Total workload in hour						
Hours of data	Hour 2-Hour 22					
	Coefficient	Std Error (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			
Ν	919					
R-Squared	0.91					
Rho_ar	0.58					

Table 3. Results of the fixed effects cross-sectional time series analysis for the CEATS Region.

The shaded rows indicate significant variables at the 5% level.

Since the cross-sectional time-series analysis gave such positive results in prediction, a second set of simulations were conducted of an area of European airspace very different to the CEATS region. This was the Mediterranean Free Flight (MFF) airspace, and the major differences in features between the two scenarios are shown in Table 4.

Figure 5. The graph of actual vs. predicted workload for the 46 sectors throughout the 20-hour day in the CEATS region.



Table 4. Major differences between the CEATS and MFF airspace regions.

Feature	CEATS Airspace	MFF Airspace
Traffic	Small-Med	Many
Transit times	Short (5mins)	Long (15 mins)
Sector Size	Small	Very Large
Neighbours	Many	Few

If the cross-sectional time-series method is appropriate, then there should be a major difference between the significant variables for the two regions, whilst still providing accurate results in prediction of the workload in both cases. The following section describes the main features of the MFF simulations.

# 8. THE MFF SIMULATION SCENARIO.

# i) The RAMS Simulation

The airspace of the MFF region was simulated, Figure 6, and consists of nine contiguous "super sectors". The traffic sample consisted of 7000 flights in 19 hours, following a standard route structure. The controller tasks and their timings used in this analysis take into account the technology and procedures used in the MFF region and were obtained from the MFF real-time simulation studies.



Figure 6. The MFF simulation region.

It includes tasks in the five main areas of controller activity accounted for in the RAMS model:

- Co-ordination tasks;
- Flight data management tasks
- Planning conflict search tasks to determine ATC clearances
- Routine Radio/Telephone communications
- Radar Tasks consisting of radar handovers and coordinations, radar supervisions, radar interventions and vectoring.

Table 5 lists the main air traffic controller input rules used for the simulation study. A detailed description of the conflict detection and resolution aspects of the RAMS simulation can be obtained from Majumdar et al. (2004).

Attribute	Planning Controller	Tactical Controller
Planning Controller Window entry/exit distance before/after sector (mins)	15 minutes	Not applicable
Radar Window entry/exit distance before/after sector (NM)	Not applicable	20
Radar Window entry/exit distance above/below sector (100's ft.)	Not applicable	20
Vertical Separation	ICAO Separation Rules	ICAO Separation Rules
-	1,000 feet below FL290	1,000 feet below FL290
	2,000 feet above FL290	2,000 feet above FL290
Lateral Separation (NM)	10.0	10.0
Longitudinal Separation (NM)	10.0	10.0

Table 5. Controller rules input data in the simulations

Detection Dynamics	Defined Detection Dynamics	Defined Detection Dynamics .
Controller Task Base	CEATS Tasks	CEATS Tasks
Controller Rule Group	Planning Rules	Tactical Rules
Entry Distribution	RAMS Default Distribution	RAMS Default Distribution*
Conflict Detection model	Rectangle	Rectangle
Sector Clipping	60 seconds	60 seconds

\*This applies to the handoff entry time to the tactical controller.

#### ii) The Controller interviews

For the MFF panel data study, a set of interviews on ten operational air traffic controllers in Europe were conducted to better determine the factors that affect controller workload rather basing this upon a literature-based. These air traffic controllers had an average of over ten years of experience, and in addition to being interviewed on the factors affecting the workload they were interviewed on how these factors actually affected their workload. The controllers were interviewed on a number of factors and the major findings are shown in Table 6, with effect one being the primary impact of that factor of the controller's workload and effect two being the secondary effect.

Factor	Effect 1	Effect 2
Aircraft speeds	Speed difference between the fastest and slowest aircraft over the entry points AND at the same Flight Level	
Entry and exit points	The combined number of entry and exit points	The ratio of entry to exit points
Number of surrounding sectors	Number weighted by flow	
Number of routes	The actual number of bidirectional/ unidirectional routes	Parallel distance of route to the sector boundary
Intersection points	Number of intersection	
Navaids	No influence	
Flight Levels	Number of Flight Levels (FLs)	
Sector Geometry	Transit times of 5-20 minutes	

Table 6. Major findings from controller interviews.

## iii) The derivation of new variables from the RAMS Simulation

Based upon the controller interviews, the independent variables used for the panel data analysis in the CEATS region, Table 2, required modification. This section will consider the development of two new independent variables for the following factors; the speed differential at entry points AND at same FL and weighting the flow from surrounding sectors

Figure 7, indicates for the Macedonia "supersector" of the MFF Region for a particular hour, both the maximum speed difference between the fastest and slowest aircraft at each flight level and the number of aircraft at each flight level. In order to account for the interview based responses of controllers as to how these factors affect controller workload a new variable for speed differential (*SD*) at different FLs each hour was derived as follows:

$$SD = \sum_{i}^{w} N_{i} S_{i}$$
(3)

Where:

 $N_i$  = number of aircraft at Flight Level *i* 

 $S_i$  = Maximum speed difference between the fastest and slowest aircraft in the hour at FL *i* 

w = Total number of flight levels used.

The larger the value of *SD*, the greater will be the impact on controller workload in controlling that situation, a fact apparent from the interviews. Figure 8 indicates how the SD variable is distributed across the flight levels in the Macedonia sector in Hour 4.

Figure 7. The maximum speed difference between the slowest and fastest aircraft in the Macedonia sector at Hour 4 at each flight level used.



Similarly a weighted value for the number of neighbouring sectors from which aircraft enter was derived to account for the weighted flows that were deemed important from controller interviews.

Figure 8 The speed differential variable in the Macedonia sector at Hour 4 at each flight level used.



Table 7 below shows the number of aircraft entering the Athens supersector of the MFF simulation over an eleven hour period. The last column of Table 7, SS Number, indicates the total number of neighbouring sectors from which aircraft enter, assuming no weighting, i.e. all aircraft entries treated equally.

Hour	BRINDISI	FEEDLOW	FEEDONE	MAKEDON	Malta	NCCSIA	NullSect	Roma	Total	SS Number
1	14	17	29	32	2	19	C	) 1	114	6
2	2 10	22	23	39	0	3	1	1	99	7
3	8 8	41	25	48	0	6	1	1	130	7
4	10	57	25	45	0	3	C	0 0	140	5
5	5 18	29	18	46	1	6	C	) 5	123	7
6	6 9	18	14	37	1	1	1	6	87	8
7	' 8	12	19	16	0	4	C	) 3	62	6
8	8 8	16	22	26	1	8	C	) 4	. 85	7
g	8	29	16	34	. 0	8	C	) 4	. 99	6
10	) 16	26	20	35	0	9	C	) 3	109	6
11	16	44	11	44	0	8	1	2	126	7

Table 7. The number of aircraft entering the Athens sector per hour from neighbouring sectors in the MFF simulation.

Given that the controller interviews indicated that controllers may control by considering the proportion of traffic flow into the sector. Therefore taking a 10% of hourly flow threshold as affecting the controller's workload, Table 8 now indicates the weighted number of surrounding sectors from which aircraft enter the Athens sector per hour in the last column.

Table 8. The percentage of aircraft entering the Athens sector per hour from neighbouring sectors in the MFF simulation.

Hour	BRINDISI	FEEDLOW	FEEDONE	MAKEDONI	MALTA	NICOSIA	NullSect	Roma	Total Sectors
1	12.28	14.91	25.44	28.07	1.75	16.67	0.00	0.88	5
2	10.10	22.22	23.23	39.39	0.00	3.03	1.01	1.01	3
3	6.15	31.54	19.23	36.92	0.00	4.62	0.77	0.77	3
4	7.14	40.71	17.86	32.14	0.00	2.14	0.00	0.00	3
5	14.63	23.58	14.63	37.40	0.81	4.88	0.00	4.07	4
6	10.34	20.69	16.09	42.53	1.15	1.15	1.15	6.90	4
7	12.90	19.35	30.65	25.81	0.00	6.45	0.00	4.84	4
8	9.41	18.82	25.88	30.59	1.18	9.41	0.00	4.71	4
9	8.08	29.29	16.16	34.34	0.00	8.08	0.00	4.04	3
10	14.68	23.85	18.35	32.11	0.00	8.26	0.00	275	4
11	12.70	34.92	8.73	34.92	0.00	6.35	0.79	1.59	3

As can be seen from the shaded columns, three sectors are ignored for sector entries. A similar variable was derived for the weighted number of surrounding sectors for which aircraft exit the Athens Sector.

#### iv) The analysis of panel data results for the MFF Scenario

Based upon a number of new variables derived from the controller interviews, together with the existing variables from Table 2, fixed-effects panel data modelling was undertaken. Table 9 outlines the most appropriate model, with the significant variables shaded. The basic features of this model are that the aircraft features, whether their profiles or the speed differential appears to be significant. Given the large sector sizes in the MFF area with few neighbouring sectors, it is not surprising that sector effects are not significant.

In particular, at the 5% level of significance, the following flight profile variables are significant:

- The number of aircraft in continuous cruise profile. Each aircraft in continuous cruise increases controller workload by 49 seconds in all sectors of the MFF region in any given hour;
- The number of aircraft with cruise-climb profile. Each aircraft with a cruise-climb increases controller workload by 134.31 seconds
- The number of aircraft with cruise-descend profile. Each aircraft with cruise-descend profile increases controller workload by 125.53 seconds
- The number of aircraft with climb-climb profiles. Each aircraft with a climb-climb profile increases controller workload by 164.83 seconds
  - The speed difference quotient increases controller workload by 0.17 seconds.

The efficacy of using the cross-sectional time series technique lies in its ability to accurately predict the workload in a sector at different times of the day, given the appropriate set of significant variables. The parameter estimates of the model from the panel data can be subsequently used for predicting the workload in a sector throughout the day. Figure 9 shows

the predicted workload obtained using the parameters for the significant variables from the model with no serial correlation compared to "actual" workload recorded by RAMS for two sectors. This graphical analysis seems to indicate a good model fit, i.e. goodness of fit, with the predicted workload curve mirroring the actual workload curve closely.

Hours of data	Hour3-H	Hour3-Hour 22		
	Coefficient	t-statistic		
Number of aircraft in continuous cruise profile	48.59	3.82		
Number of aircraft in cruise-climb profile	134.31	6.43		
Number of aircraft in cruise-descend profile	125.53	7.91		
Number of aircraft in descend-descend profile	70.53	1.51		
Number of aircraft in descend-climb profile	145.85	1.84		
Number of aircraft in climb-climb profile	164.83	3.04		
Speed difference quotient	0.17	2.74		
Constant	343.33	1.02		
Ν	180			
R-Squared	0.87			
Rho	0.64			

# Table 8. The panel data results from the MFF simulation. **Dependent variable = Total workload in hour**



Figure 9 The graph of actual vs. predicted workload for the 9 sectors through an 11-hour period in the MFF region.

# 9. Conclusions

En-route airspace capacity in Europe is primarily determined by controller workload. This paper has indicated that the cross-sectional time-series analysis of a simulated region of airspace can be a useful method by which to study the factors affecting controller workload throughout the day, and to predict this workload. It has also highlighted that the variables that best describe the controller workload in the peak hour seem to differ from those throughout the day. This is important since there appears to be a "peak spreading" effect in daily traffic rather than pronounced peaks in European air traffic.

Cross-sectional time-series analysis of two dissimilar regions of European airspace has captured main features captured. In the CEATS region, aircraft and sector features were found to be significant, whilst in the MFF region aircraft features only were significant. Therefore this method seems to capture the essential elements that are expected to affect controller workload in these areas. In that sense, it joins methods such as dynamic density (Laudemann et al. 1998) in permitting a prediction of controller workload given a number of airspace and aircraft features. The use of controller interviews has better enabled these factors to be identified.

Given the strong predictive abilities of the analysis, there is a need to undertake further analysis of this method to ensure its robustness, e.g. introducing non-linear methods. Finally it should however be noted that the research presented here has been based on simulated data, i.e. an analytical model based upon the output of a simulation model. As such, this is a good initial step in obtaining the drivers of workload and operational data is needed for thorough validation of the results, assuming enough of such data could be obtained for statistical adequacy.

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