

An Analysis of the Spatio-Temporal Factors Affecting Aircraft Conflicts Based on Simulation Modelling

Arnab Majumdar, Research Associate, Centre for Transport Studies Imperial College
London, London, United Kingdom,

Washington Ochieng, Senior Lecturer, Centre for Transport Studies Imperial College,
London, London, United Kingdom,

Robert B. Noland, Imperial College London, London, United Kingdom

The demand for air travel worldwide continues to grow at a rapid rate, especially in Europe and the United States. In Europe, the demand exceeded predictions with a real annual growth of 7.1% in the period 1985-1990, against a prediction of 2.4%. By the year 2010, the demand is expected to double from the 1990 level. Within the UK international scheduled passenger traffic is predicted to increase, on average, by 5.8 per cent per year between 1999 and 2003. The demand has not been matched by availability of capacity. In Western Europe many of the largest airports suffer from runway capacity constraints. Europe also suffers from an en-route airspace capacity constraint, which is determined by the workload of the air traffic controllers, i.e. the physical and mental work that controllers must undertake to safely conduct air traffic under their jurisdiction through en-route airspace.

The annual cost to Europe due to air traffic inefficiency and congestion in en-route airspace is estimated to be 5 billion US Dollars, primarily due to delays caused by non-optimal route structures and reduced productivity of controllers due to equipment inefficiencies. Therefore, to in order to decrease the total delay, an increase in en-route capacity is of paramount importance. At a global scale and in the early 1980s, the International Civil Aviation Organisation (ICAO) recognised that the traditional air traffic control (ATC) systems would not cope with the growth in demand for capacity. Consequently new technologies and procedures have been proposed to enable ATC to cope with this demand, e.g. satellite-based system concept to meet the future civil aviation requirements for communication, navigation and surveillance/ air traffic management (CNS/ATM). In Europe, the organisation EUROCONTROL (established in 1960 to co-ordinate European ATM) proposed a variety of measures to increase the capacity of en-route airspace. A key change envisaged is the increasing delegation of responsibilities for control to flight crew, by the use of airborne separation assurance between aircraft, leading eventually to 'free flight' airspace. However, there are major concerns regarding the safety of operations in 'free flight' airspace.

The safety of such airspace can be investigated by analysing the factors that affect conflict occurrence, i.e. a loss of the prescribed separation between two aircraft in airspace. This paper analyses the factors affecting conflict occurrence in current airspace and future free flight airspace by using a simulation model of air traffic controller workload, the RAMS model. The paper begins with a literature review of the factors that affect conflict occurrence. This is followed by a description of the RAMS model and of its use in this analysis. The airspace simulated is the Mediterranean Free Flight region, and the major attributes of this region and of the traffic demand patterns are outlined next. In particular a day's air traffic is simulated in the two airspace scenarios, and rules for conflict detection and resolution are carefully defined. The following section outlines the framework for analysing the output from the simulations, using negative binomial (NB) and generalised negative binomial (GNB) regression, and discusses the estimation methods required. The next section presents the results of the regression analysis, taking into account the spatio-temporal nature of the data. The following section presents an analysis of the spatial and temporal pattern of conflicts in the two airspace scenarios across a day, highlighting possible metrics to indicate this. The paper concludes with future research directions based upon this analysis.

1. INTRODUCTION

Air traffic controllers play a vital role in ensuring that all aircraft under their jurisdiction maintain a safe separation in the airspace through which they pass. This airspace is divided into air traffic control (ATC) sectors, which are geographical volumes of airspace. Controllers are assisted in their duties by both technology and international regulations. The rapid growth in European air traffic has highlighted the increasingly critical role of the controllers e.g. in the period between 1985-1990, air traffic in Europe increased by 7.1% annually (EUROCONTROL, 1991). In 1990, 90% of the flights recorded within Western and Central Europe were internal to the area, i.e. there were 4.8 million flights across or within Europe in just that year. Furthermore, this air traffic is unevenly distributed throughout Europe, with the existence of a "core area", consisting essentially of London-Brussels-Frankfurt-Milan (including Paris) area, where air traffic density is greatest. Forecasts indicate both (ATAG, 1992) a 110% growth in European air traffic between 1990 and 2010 resulting in 11 million flights per year over Western Europe in 2010; and an increase in the size of the "core area" by 2010. Consequently controllers in the "core area", already very busy, will have to control many more aircraft in the future.

The major problem that underlies Europe's current airspace organisation is the lack of a single, integrated ATC system. Each European nation controls and manages its ATC infrastructure and the air traffic within its sovereign airspace. This leads to incompatibilities in technology as well as to the duplication of tasks and information across Europe. Amongst the major implications of these two factors are; a rise in flight delays in Europe, non-optimal flight profiles, extra route lengths and possible safety implications. The economic impact of delays, as well as other inefficiencies in the ATC system (e.g. non-optimal flight profiles), has been estimated to cost Europe US \$5 billion a year (Lange, 1989; The Financial Times, 1999).

In the late 1980s, at the request of the Transport Ministers of the European Civil Aviation Conference (ECAC), the European Organisation for the Safety of Air Navigation (EUROCONTROL) developed the European Air Traffic Control Harmonisation and Integration Programme (EATCHIP) (EUROCONTROL, 1991) to tackle the airspace capacity problems (ECAC, 1990). EATCHIP aimed to progressively harmonize and integrate the diverse ATC systems throughout Europe by using a combination of new technology (both in the control room and in the air, such as the use of mandatory area navigation equipment on aircraft to provide greater precision in position than currently available) and innovative control procedures, such as the flexible use of airspace between civil and military ATC.

Many of the objectives of EATCHIP have been achieved and it has had some success in reducing the capacity problem, e.g. there has been a 40% increase in capacity since 1990 to cope with a 35% increase in air traffic during the same period (ECAC, 1998). However, the delays have not disappeared e.g. the average flight delay caused by air traffic control problems from January through to October 2000 was 3.9 minutes (Flight International, 2000). The continued growth in European air traffic has led EATCHIP to be succeeded by the EATMP (European Air Traffic Management Programme) (EUROCONTROL, 1998). The main characteristic of EATMP is the "gate-to-gate" concept, in which

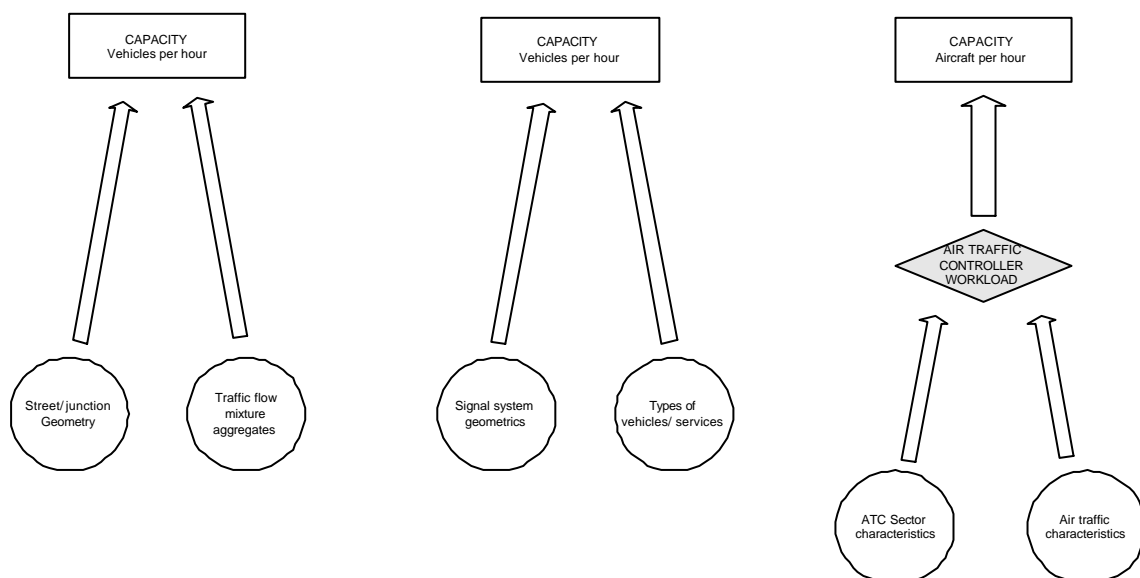
flights are treated as a continuum from the first interaction with ATM until post-flight activities. In order to achieve this, a broad range of measures and a variety of technologies are considered that may significantly alter the way in which controllers will work in the future European ATC system.

The success of the any initiative to increase airspace capacity, both currently and in the future, depends upon a reliable definition and measure of airspace capacity. In a dense air traffic network, such as that seen in Europe, this must take into account both the workload of the air traffic controllers and the aircraft performance-related spatial separation criteria. A crucial element of the workload of air traffic controllers is the work they must undertake in order to detect and resolve conflicts between aircraft in airspace.

This purpose of this paper is to provide a framework by which to analyse the factors affecting conflict occurrence in Europe's en-route airspace, using a simulation model of the air traffic controller's workload. The paper is organised as follows. Section 2 examines the intricacies involved in the understanding and measurement of airspace capacity and its link to controller workload. Section 3 reviews the literature on the factors affecting controller workload by various methods, and notes that there exists an opportunity to estimate airspace capacity using a simulation model of controller workload. Section 4 discusses controller workload models in light of their appropriateness for such a simulation based study, and Section 5 considers one for further usage, the Re-organized ATC Mathematical Simulator (RAMS) (EUROCONTROL, 1996 a and b), in a series of simulation experiments. Section 6 then outlines a scheme for estimating the factors affecting conflict count using a simulation model of controller workload, whilst Section 7 describes the simulation experiments. Section 8 outlines a general analytic framework using the output from the simulation model to estimate the factors affecting conflict count and noting in particular the need to use negative binomial and generalised negative binomial models. Section 9 concludes the paper.

2. AIRSPACE CAPACITY AND CONTROLLER WORKLOAD.

In surface transport, capacity is relatively easy to understand. For example, the capacity of a road link is the maximum flow through that link for a particular period of time. This maximum flow is



influenced by both the spatial-geometrical constraints, e.g. road geometry, and the composition of the road traffic, i.e. the mix of cars and heavy goods vehicles (HGVs). Furthermore, this maximum flow can be delivered by alternative demand patterns. The capacity of a railway link is likewise determined by both spatial-geometrical criteria and rail traffic composition criteria.

Figure 1. The difference between surface transport and airspace capacity criteria.

The experience of a high air traffic density region, such as Europe, suggests that a more appropriate and safer measure of airspace capacity must incorporate air traffic controller workload i.e. the mental and physical work done by the controller to safely control traffic. This is in addition to the spatial separation criteria between aircraft, based upon their performance, and the traffic mix in the sector. Therefore it is controller's workload threshold that determines the capacity of an ATC sector, Figure 1.

With this in mind, the capacity of an ATC sector can be defined as the *maximum number of aircraft controlled in that ATC sector in a specified period of time*, whilst still permitting an *acceptable level of controller workload*. This maximum number of aircraft concerns those aircraft whose control generates work for the controllers, and includes aircraft entering, exiting and transiting through the sector, in a given period of time. Based upon such a capacity definition, there is then a need to determine:

- ?? what is meant by controller workload?;
- ?? how is this controller workload measured?;
- ?? what is the acceptable level of controller workload, i.e. the threshold value at capacity?

Controller workload is a confusing term and with a multitude of definitions and models in the literature, its measurement is by no means uniform (Jorna, 1991). Workload is a construct, i.e. a process or experience that cannot be seen directly, but must be inferred from what can be seen or measured. The research, theory, models and definitions of workload are inter-related and there are numerous reviews of workload and its measurement (e.g. Gawron et al. 1989). Whilst there are a variety of methods for measuring air traffic controller workload (Hopkin, 1995), essentially they can be performed either by self-assessment of the controllers whether instantaneous, e.g. the SWAT (Wickens, 1992) technique, or non-instantaneous, e.g. the NASA-TLX method (Hart et al. 1988); or by direct observations of the controllers whether by other controllers or ATC system experts, i.e. detailed non-intrusive techniques.

There is an important methodological dimension in the two major measurement approaches, in that one method is self-assessed whilst the other is observer assessed. However, two major problems arise with these measurement techniques. One is that apart from the non-intrusive controller observations, which can be made in an operational ATC scenario, these techniques can only be conducted practically during "real-time" simulations, i.e. when the controllers control simulated air traffic in mock-up facilities. The other is that both the controller self-assessment and the observer rating of workload techniques introduce a degree of subjectivity bias in the controller workload measure.

The experience of airspace capacity analysis in Europe suggests that the most appropriate measure for controller workload is that based upon the tasks (both physical and mental) and their timings that the controller must do in order to control air traffic (Stamp, 1992). Such a measure can be thought of as a *task-time measure of controller workload*. The most preferred method by which this task-time measure of controller workload can be obtained is by a *detailed non-intrusive objective record of the controller's actions*. However, in order to properly account for the non-observable cognitive tasks of a controller, e.g. planning, this record needs to be supplemented by controller verification of the tasks and their timings. By this method, it is possible to better account for the time controllers spend in the thinking and planning component of their tasks and thereby ascertain the “true execution time” for each task (Lyons and Shorthose, 1993).

Of interest to this research is to consider what tasks will comprise this task-time measure of controller workload. The essential tasks for air traffic control, tasks can be summarised as (Dee, 1996):

- ?? plan future “streams” of aircraft;
- ?? check future streams do not conflict within sector;
- ?? determine how to resolve conflicts;
- ?? acknowledge aircraft coming onto their frequency;
- ?? instruct aircraft to manoeuvre to avoid conflicts;
- ?? assure aircraft arrival at the planned sector exit point, level and;
- ?? co-ordinate their actions with adjacent sectors;
- ?? monitor aircraft behaviour for deviations from plan;
- ?? hand aircraft to the next sector;
- ?? comply with special requests and handle emergencies;

Therefore, for any air traffic controller workload model to be effective for the planning and design of airspace, it must model the above essential tasks in the most appropriate way possible. In particular the tasks involved in detecting conflicts between aircraft and the resolution of such conflicts are amongst the most crucial to model.

Another factor that must be considered is that these tasks need to be discriminated by the type of controller performing them. In the current European air traffic organisation, there is usually a team of two controllers, a planning controller (PC) and a tactical or radar controller (TC). Their duties are outlined below, Table 1. Note that the components of each task and its timing will depend upon the level of technology present in the sector, from basic to a high level of automation.

Table.1. The roles of the planning and tactical controller

Factor	Planning Controller	Tactical Controller
<i>Aircraft considered</i>	Aircraft entering into and exiting from sector.	Only aircraft within the sector.
<i>Time Frame</i>	15-20 minutes look ahead.	5-10 minutes look ahead.
<i>Coordination requirements</i>	With TC within sector and PCs of adjacent sectors.	Primarily with PC of the sector.
<i>Prime Task</i>	Agree exit/entry conditions with adjacent sectors.	Maintain specified aircraft separation distances.

Given the importance of conflict-related tasks for the controller, it is possible to consider the number of conflicts in a sector as a proxy measure of the controller's workload. The advantage of this method is that there is no need to determine the exact tasks that controllers must do and their timings. Magill (1998) uses such a method in his simulation model based research of airspace capacity in Europe.

3. AIRSPACE CAPACITY DRIVERS.

Research studies (Mogford et al., 1995) indicate that it is the complex interaction of the air traffic and the characteristics of the ATC sectors through which that air traffic flies, that generates the workload experienced by air traffic controllers – however this is defined and measured. These can therefore be thought of as the *primary or source factors of the workload*. In addition, the workload experienced by the controllers can be mediated by the *secondary factors* that include: the cognitive strategies the controller uses to process air traffic information; the quality of the equipment (including the computer-human interface) and individual differences (such as age and amount of experience). These factors can be thought of as the drivers of controller workload, and consequently of airspace capacity, i.e. *airspace capacity drivers*. The effect of these factors on airspace capacity must be understood if realistic and successful strategies for increasing capacity are to be implemented. Figure 2. illustrates a model proposed by Mogford et al. (1995) of controller workload based upon these four factors.

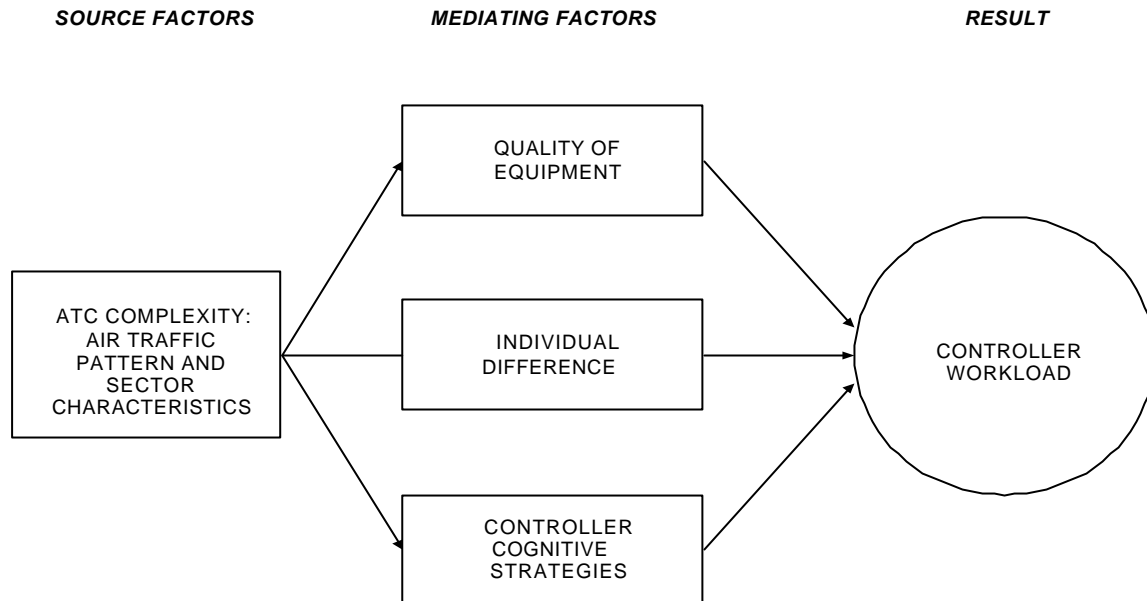


FIGURE 2: FACTORS AFFECTING CONTROLLER WORKLOAD
Source : Mogford et al. (1995), page 5

Mogford et al. (1995) provide a useful review of research, on the effect of these factors on controller workload. There have also been various recent attempts in the USA and Europe to understand the relationship between controller workload and a number of these workload drivers. The methodologies for such attempts fall into two broad categories, either:

1. “real-time” simulations followed by controller questionnaires, e.g. the “dynamic density” concept of NASA (Laudemann et al., 1998; Sridhar et al., 1998) . Whilst aided by major controller involvement, these studies are expensive and time-consuming; or
2. the analysis of historic data e.g. by the FAA human factors group (Rodgers et al., 1998) on the separation loss between aircraft, assumed to occur when controllers are under high workload conditions, in the Atlanta airspace sectors. Whilst such a study is of great use, concerns arise about the transferability of the results to other airspace sectors as well as its limited use in studying future technology and procedural scenarios.

These two approaches have provided significant insights on the parameters influencing controller workload and airspace capacity, Table 2. However, both methods have problems their authors note.

In addition, Table 3 indicates the factors that affect conflict occurrence in European airspace, a matter investigated in Europe’s efforts to organise its airspace as a single airspace (Fischer and Seaman, 2002).

An alternative approach is the use of computer simulation modelling of airspace and controller workload to systematically vary a number of possible air traffic and ATC sector parameters, i.e. carefully define the rules for the elements of the simulation in order to investigate their interaction.

Subsequent analysis of the output from the model can be used to formulate a functional relationship between the controller workload and the relevant parameters at an aggregate level. Whilst various studies have been undertaken using simulation models of controller workload (e.g. EUROCONTROL, 1997), none has considered the impact of systematically varying a set of air traffic and ATC sector parameters on workload and then formulating a functional relationship. Magill (1997, 1998) notes the advantages of a simulation modelling technique over real-time simulations for capacity estimation in particular its economic benefits, its use over a large geographical area and its ability to investigate a wider range of traffic levels. To use such a computer simulation methodology, it is imperative to choose the appropriate controller workload simulation model. The following section describes alternative workload models in light of their appropriateness for the simulation modelling approach.

Table 2. List of air traffic and sector factors that can affect ATC complexity and controller workload from the literature.

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

Table 3 - Factors contributing to conflict complexity.

Source: Fischer and Seaman (2001)

Factor	Notes
Vertical mix	One aspect of conflict geometry
Relative bearing	Another aspect of conflict geometry
Agility mix	Controllers state that the mix of aircraft types has a large effect on the complexity of a conflict. Aircraft types are classified as either “agile” or “not agile”
Separation at CPA	The closest approach of the conflict.
Number of surrounding aircraft	The number of aircraft within 40nm and 1000ft of the midpoint of the conflict event at the CPA time.
Edge distance	If aircraft are close to the sector boundary then the controller must consider the involvement of aircraft which are outside the sector.
Aircraft on frequency	The total number of aircraft under the control of the tactical controller.
Potential conflicts	The number of potential conflicts at the time of the conflict event.
Crossing points	The number of nodes of potential conflicts in the sector.
Rate of arrival	The number of aircraft arriving in the 10 minute interval around the time of the conflict event.
Size and shape	This captures information about the time available to manoeuvre aircraft in the sector.

4. CONTROLLER WORKLOAD MODELS

Air traffic controller workload models can be either analytic or simulation models. Analytic models are based on relatively straightforward equations, often regression equations, in which the predicted output

can be rapidly generated from the mathematical analysis of a specified set of inputs. Two examples of analytic controller workload model are the Sector Design Analysis Tool (SDAT) devised in the USA (Geisinger and MacLennan, 1994), and the Capacity indicators Model (CIM) used by EUROCONTROL (Lyons and Shorthose, 1993). Both these models determine the workload in a sector given the associated sector tasks and use probability theory to predict the expected number of conflicts in the sector and the consequent resolution strategies to resolve them.

Simulation models are more complex. Given the inputs and a number of operating rules, the computer model simulates events over time and generates a set of performance outputs, typically probabilistic ones (EUROCONTROL, 1996a). Simulation models are useful when the modelled variables have a range of values (e.g. the distribution of air speeds) and system performance must be evaluated with elements that vary across this range.

In general, simulation models are often necessary in a system such as air traffic control since the great complexity of the system prevents its behaviour from being captured by analytic equations (Wickens et al., 1997). In addition, the inherently dynamic behaviour of the airspace is well suited for a dynamic simulation. There are two major simulation controller workload models. One of these is the DORATASK model (Stamp, 1992) that has been developed and used specifically for the UK's ATC sectors, where its results have been validated. The other is the Re-Organized ATC mathematical Simulator (RAMS) that has been widely used and validated throughout European airspace (EUROCONTROL, 1995). In addition, a model of air traffic controller workload based upon the cognitive tasks of a controller is now being developed by NATS, known as the Performance and Usability Modelling in ATM (PUMA) Model (Kilner et al., 1998).

Table 4 outlines the main features of the analytic and simulation controller workload models outlined above. Based upon the previous discussion and the features outlined in Table 4, it would seem that the most appropriate simulation model for use in conducting airspace capacity assessments over a large region of European airspace is the RAMS model. The main features of RAMS are outlined below together with a discussion of the issues that must be taken into account in any simulation exercise.

5. THE REORGANIZED ATC MATHEMATICAL SIMULATOR (RAMS)

The RAMS model is a discrete-event simulation model that has been used widely for over 25 years in Europe for airspace planning, and has been verified by controller use (EUROCONTROL, 1999a). In the RAMS model, each control area is associated with a sector, which is a 3-dimensional volume of airspace as defined in the real airspace situation. Each sector has associated with it a RAMS Planning Control and a RAMS Tactical Control, Figure 3. These control areas maintain information regarding the flights that wish 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. The use of the Planning and Tactical control elements reflects the teamwork aspect of control seen in practice. The simulation engine also permits the input of rules for these controllers that mimics reality. The tasks for the

controllers in RAMS are based on a total of 109 tasks undertaken by controllers, together with their timings and position, grouped into five major areas. These tasks are derived from a number of reference airspace regions of Europe, which include sectors in the London region, Benelux countries, France and Germany. Furthermore, a cloning engine enables future traffic demands to be generated, based upon the current air traffic patterns.

A range of methodological issues must be addressed with the use of such a simulation modelling technique, especially the need to ensure that the simulation replicates the conditions in European airspace as closely as possible. Figure 4. shows the major inputs and outputs of the RAMS model. The application of appropriate “rules” for the inputs of RAMS, deals with the following simulation issues:

- ?? the area of airspace simulated - the characteristics of the ATC sectors and the air routes through them, are contained in the sector data input files;
- ?? the air traffic simulated - the characteristics of the aircraft and their performance capabilities are contained in the air traffic data input files;
- ?? the simulated controller tasks and procedures - the set of controller’s tasks and their timings are contained in the controller task input files. The choice of an appropriate set and its implications are of the utmost importance in both undertaking as well as understanding the simulation results.

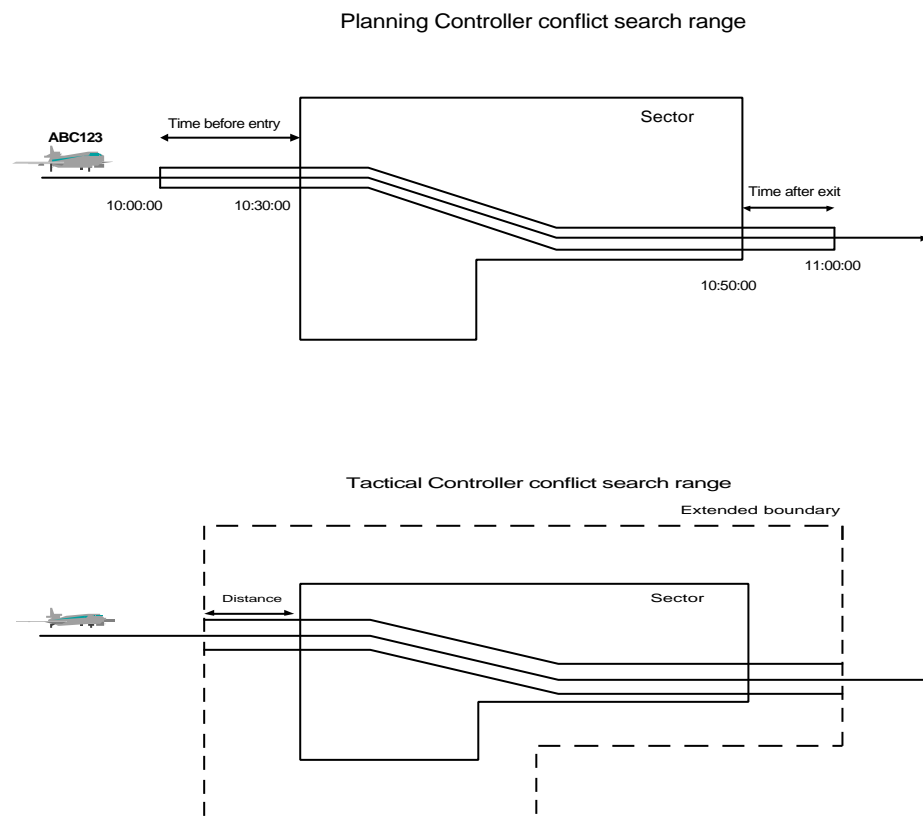


Figure 3. The control elements in RAMS.

Having ensured that RAMS reflects the real airspace environment being simulated as closely as possible, attention must then be paid to the workload estimates from the model. Magill (1998) notes

that to make effective use of the simulation modelling technique, “it is desirable to have a simple means to characterise the work done by the ATC system” (page 2). The workload estimates obtained from the RAMS model are based upon on task-time definitions derived from a detailed non-intrusive objective record of the controller’s actions, aided by controller verification. Based upon these task-time definitions, threshold controller loadings of a control team (Tactical and Planning) at capacity being 42 minutes/hour loading must be utilised for RAMS (EURCONTROL, 1999a). This task time threshold has been validated by several real-time studies and the experience gained from previous simulation results, as well as from field studies (EUROCONTROL 1999a, 1999b, 1999c).

Given that this workload measure includes only a measure of the physical and the mental demands on the controller, it is more appropriate to deem the measure as the taskload for the controller. For the purposes of continuity the term controller workload will still be used to depict this taskload.

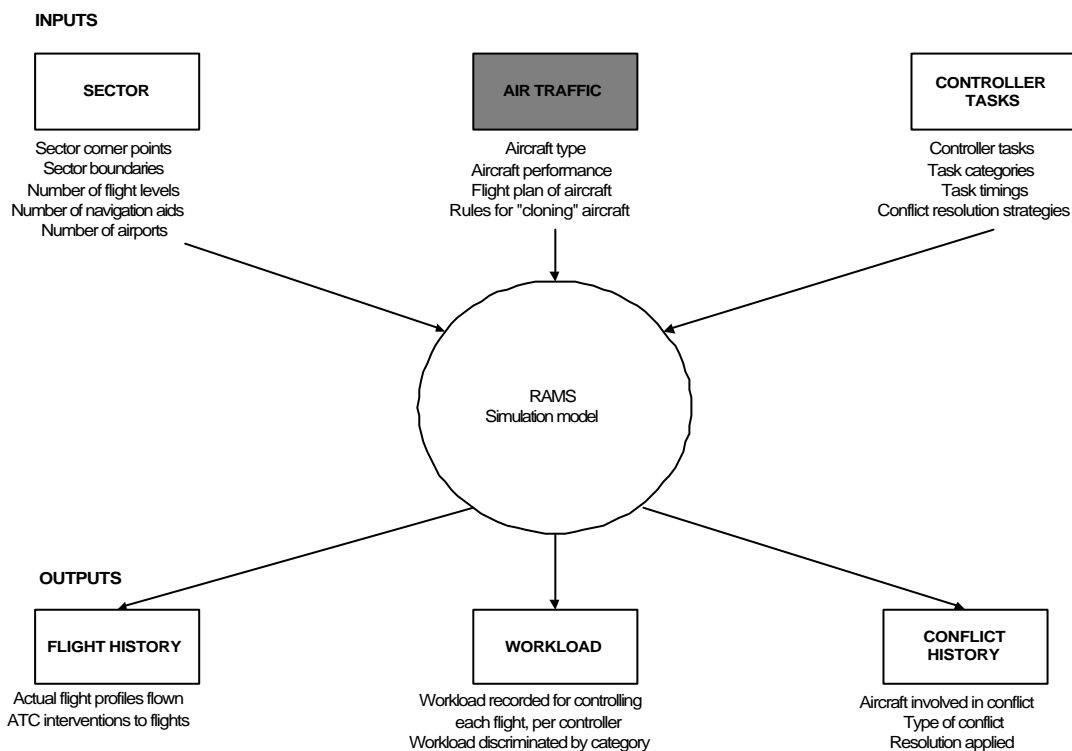


Figure 4. The inputs and outputs into the RAMS model.

6. A SCHEME FOR ESTIMATING AIRSPACE CAPACITY BASED ON CONTROLLER WORKLOAD SIMULATION MODELLING.

Based on the previous sections, it is possible to generate a perfectly adequate general capacity model, using the following procedure, summarised by Figure 5:

Step 1: Define the physical characteristics of the air traffic system. This is conceptually simple for the existing ATC network. There is a need to define:

- ?? the airspace sectors and their horizontal and vertical boundaries (locations);
- ?? the number of flight levels in each sector;

- ?? the air routes through the sectors, comprising of a series of navigation aids defined by geographic coordinates;
- ?? the airport locations, in geographic coordinates

Whilst these are directly observable, data collection and analysis can be time consuming.

Step 2: Define the traffic demand through the sectors. This involves definition of the aircraft types and their associated performance characteristics, e.g. speed characteristics, climb and descend rates, as well as their chosen routes. This also applies for the any traffic demand forecast known.

Step 3: From the output of the simulation runs, undertake statistical analysis to derive a functional relationship between the conflict count data in the sectors and the factors that could affect it, mentioned in Section 3.

7. THE SIMULATION EXPERIMENTS.

The study was conducted for the CEATS en-route airspace (Figure 1). The Reorganized ATC Mathematical Simulator (RAMS) was used in this study (Figure 2). The controller workload was simulated with the RAMS software based on inputs including:

- ?? Sectorisation
- ?? Traffic
- ?? Controller input
- ?? Conflict detection

7.1. Sectorisation

The major sector input files are listed in Table 1. The airspace of the CEATS region consists of 46 contiguous sectors with 13 Area Control Centres (ACCs).

7.2. Traffic

The main traffic input files are listed in Table 2. The traffic sample used consisted of 5400 flights in 20 hours, following a standard route structure.

7.3. Controller Input

Table 3 lists the main air traffic controller input rules used for the simulation study, whilst Table 4 outlines the main controller input files. The controller task base accounts for the technology and procedures used in the CEATS area. It includes tasks in the five main areas of controller activity accounted for in the RAMS model:

- ?? Co-ordination tasks consisting of external communications with other ATC units and internal coordination within the simulated ATC unit
- ?? 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.

7.4. Conflict Detection

Conflict detection and resolution are major elements of the controller's tasks. The following parameters were used for conflict detection between aircraft:

~~///~~ Vertical separation – conventional vertical separation minima (CVSM) of 2,000 feet above Flight Level (FL) 290, i.e. 29,000 feet and 1,000 feet below FL 290.;

~~///~~ Horizontal separation – lateral and longitudinal separation of 10 nautical miles between aircraft.

The horizontal and vertical separation parameters outlined above create a conflict zone around the flight, rather like a tunnel when projected through time. A rectangle conflict zone was used in the simulations, Figure 3.

Dynamic separation multipliers usually increase¹ the separation between aircraft based upon the relative positions between the two flights. These multipliers rely on the dynamic situation of the flights during the simulation, not on the static values defined by airspace and aircraft type and provide increased realism into the conflict detection, i.e. they attempt to model the behaviour of real controllers.

Dynamic detection multipliers were used for realistic conflict detection in the simulation. The parameters used for this detection are outlined in Table 5, (see also Figure 5). The values chosen reflect the fact that much greater separation is required between two aircraft approaching each other on their flight paths, as opposed to diverging away on parallel flight paths. As an example, consider two aircraft in cruise, at the same flight level and on the same flight path, Figure 4. Figure 4 a), shows the aircraft following each other at constant speed. In this case the only requirement is for the prescribed longitudinal separation of 10 nautical miles. There should be no conflict detected if the aircraft maintain their constant speeds. However when the two aircraft approach each other, as in Figure 4 b), and the same longitudinal separation minima is applied, a potentially serious problem arises in the “real world” air traffic scenario. The RAMS simulation will only detect a conflict when an aircraft enters another's conflict detection zone and then propose a resolution. If such a situation were to occur in reality, a conflict between the two approaching aircraft would be detected only when it is too late for any resolution action to be successfully taken. Controllers would never allow such a situation to occur, and hence would allow for much greater separation in such a head-on approach, to allow for conflict resolution manoeuvres. This is modelled in RAMS by detection dynamics, Figure 4 c).

It is important to note that these multipliers were used *only for the longitudinal separation parameter* for each aircraft, and not for the lateral or the vertical separation parameters. This reflected the experience of previous RAMS simulations using such multipliers (EUROCONTROL, 1996).

¹ These separation multipliers can also reduce the separation between aircraft, e.g. for aircraft flying at the same level on approach routes to parallel runways, where lateral separation can be reduced.

8. PANEL DATA METHODOLOGY

An econometric method that accounts for both heterogeneity and time is the cross-sectional time-series, or “panel data” analysis (Baltagi, 1995). Panel data refers to the pooling of observations on a cross-section of households, countries, firms etc. 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 (Baltagi 1995):

1. Controlling for individual heterogeneity. Panel data suggest that individuals, countries and in the case of airspace research, ATC sectors, are heterogeneous. Time-series and cross-section studies, which do not control for this heterogeneity, run the risk of obtaining biased results.
2. Panel data give more informative data, more variability, less collinearity among the variables, more degrees of freedom and more efficiency. Time-series studies suffer considerably from high collinearity in the data. This is less likely with a panel across ATC sectors since the cross-section dimension adds a lot of variability, adding more informative data. With more informative data, reliable parameter estimates can be produced.
3. Panel data are better able to study the dynamics of adjustment. Cross-sectional distributions that look relatively stable, hide a multitude of changes. Only panel data can relate the experience and behaviour of an individual sector at one point in time to other experiences and behaviour at another point in time.
4. Panel data are better able to identify and measure effects that are simply not detectable in pure cross-sections or pure time-series data.
5. Panel data models allow us to construct and test more complicated behavioural models than purely cross-section or time-series data.
6. Panel 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.

Based upon the above, a panel data (i.e. cross-sectional time-series) analysis on the basis of the output of the RAMS CEATS simulation seems an appropriate method for estimating the functional relationship between controller workload and its drivers, i.e a number of possible independent variables, outlined in Table 7.

This RAMS simulation output data can be analyzed using a fixed effects time-series cross-sectional 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 certain conditions, 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:

$$y_{it} = \alpha_i + x_{it}'\beta + \epsilon_{it} \quad (1)$$

the error term ϵ_{it} is assumed to be independent and identically distributed over individuals i (i.e. the ATC sectors) and time, with mean zero and variance σ^2 (Verbeek 2001). The workload in sector i in time t is y_{it} and β 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 . The α_i thus capture the effects of those variables that are peculiar to the i -th individual and that are constant over time. The α_i are treated as N fixed unknown parameters. After fitting a model, there is then a need to for diagnostic testing to ensure the appropriate model has been selected.

a) The Conflict Count Situation and the negative binomial model.

In our analysis, the dependent variable y_{it} in equation (2) is not workload, but conflict count in sector i in time t . One of the features of the number of conflicts in a sector data is that it is count data and therefore is not normally distributed (Cameron and Trivedi, 1998). Therefore, either a Poisson or negative binomial model has the correct distributional properties for model estimation. Poisson distributions assume the variance is equal to the mean, a condition that is frequently violated and is known as overdispersion. Negative binomial models provide are a generalization of the Poisson model that can account for this (Miaou, 1994; Shankar et al., 1995; Vogt and Bared, 1998). Although the source of overdispersion in count data cannot be distinguished, its presence can be adjusted by introducing a stochastic component in the log-linear relationship between the expected numbers of accident in an observation unit i , λ_i and the covariates X

$$\ln \lambda_i = X_i\beta + \epsilon_i \quad (2)$$

where β is a vector of estimable coefficients representing the effects of the covariates. ϵ_i is a random error that is assumed to be uncorrelated with X . One can think of ϵ_i either as the combined effects of unobserved variables that have been omitted from the model (Gourieroux et al. 1984) or as a source of pure randomness (Hausman et al. 1984). In the Poisson regression model, variation in λ_i is introduced through observed heterogeneity. Different values of X results in different values of λ_i . In the negative binomial model, variation λ_i is due both to variation in X among individuals but also due to unobserved heterogeneity introduced by ϵ_i .

The probability density function for the NB distribution can be expressed as

$$\Pr(n_{it} | \mu_{it}, k) = \frac{\binom{n_{it} + 1/k - 1}{n_{it}} k^{n_{it}} (1/k)^{1/k}}{(1/k)^{n_{it} + 1/k} (1 + k)^{n_{it} + 1/k}} \quad (3)$$

in which $k (> 0)$ is often referred to as the overdispersion parameter. If k goes to zero then the negative binomial model reduces to the Poisson regression model. In this way, the Poisson regression model is nested within the NB and t -tests for $k=0$ can be used to evaluate the significant presence or amount of overdispersion in the data.

Considerable evidence of the intricacies involved in modelling using Poisson regression models can be seen from analysis of road accident data. The overdispersion parameter (k) determines the relative weights given to the model prediction and accident record. When fitting models to accident counts it is often assumed that one overdispersion parameter is common to all entities (i.e., road sections, intersections, wards, cities, states etc). A single overdispersion parameter is used by many researchers e.g., Maycock and Hall (1984) to model accident at roundabouts, by Hausman et al. (1984) to model patent counts, Hauer et al (1989) to model accidents at signalised intersections. To use overdispersion parameter that is common to all entities may be found limiting. There is no reason to expect that gamma distribution is the same for all entities that make up the data for regression, or to all the entities to which the predictions may be thought to apply (Hauer, 2001).

One way to overcome this is to assume that k itself is a function of various covariates and unknown parameters. Heydecker and Wu (1999) used this approach when modelling accidents at three arm junctions. The attraction of such a generalization is that it can better represent the relationships within the data.

A generalized negative binomial model can be used that allows k to vary from observation to observation as a linear combination of another set of covariates such that,

$$\ln k = \beta Z_i \quad (4)$$

where Z_i is a set of covariates and β is the coefficient to be estimated. For all models maximum likelihood techniques are used to estimate model coefficients (i.e., β) and model parameters (k).

Therefore for this analysis of conflict count in a sector data, estimates using both the NB and generalized NB (G-NB) models are required. Figure 5 outlines the analytical framework.

8. PANEL DATA METHODOLOGY

This paper has indicated the importance of considering factors that affect conflict count in en-route airspace. In addition, the use of a simulation of controller workload methodology has been postulated, in particular, using the RAMS workload model. Finally, the need to use the both the NB and generalized NB (G-NB) models are required in a panel data analysis have been outlined.

References

ATAG (1992) *European traffic forecasts*, ATAG: Geneva, Switzerland.

- Baltagi, B.H. (1995) *econometric analysis of panel data*, John Wiley & Sons Ltd, Chichester, England:UK.
- Cameron, A.C. and P.K. Trivedi (1998) *Regression analysis of count data*, Cambridge University Press, Cambridge, U.K.
- Cliff A.D. and V.K. Ord (1981) *Spatial processes: models and applications*, Pion, London
- The Daily Telegraph. (1999) Four planes a week in near-misses over Britain, September 16, pg 15.
- ECAC (1990) *ECAC Strategy for the 1990s*, ECAC, Paris.
- ECAC (1998) Integrating air traffic management - the European experience, Paper presented by 36 Contracting States of ECAC to the World-wide CNS/ATM Systems Implementation Conference, Rio de Janeiro, May 1998.
- EUROCONTROL (1991) European Air Traffic Control Harmonization and Integration Programme (EATCHIP), Phase 1 Report, EUROCONTROL, Brussels, Belgium.
- EUROCONTROL EXPERIMENTAL CENTRE (1995) RAMS system overview document, Model Based Simulations Sub-Division, EUROCONTROL, Bretigny-sur-Orge, France
- EUROCONTROL EXPERIMENTAL CENTRE (1996 a) RAMS User Manual Version 2.1, EEC/RAMS/UM/OO13, Model Based Simulations Sub-Division, EUROCONTROL, Bretigny-sur-Orge, France.
- EUROCONTROL EXPERIMENTAL CENTRE (1996 b) Evaluation of RAMS version 20, Internal EEC Note No. 1, EEC Task BM12, Model Based Simulations Sub-Division, EUROCONTROL, Bretigny-sur-Orge, France.
- EUROCONTROL EXPERIMENTAL CENTRE (1996 c) AMS (Air Traffic Control Model Simulation Studies) - an introduction for potential users, Internal EEC Note No. 2/AMS/1996, Model Based Simulations Sub-Division, EUROCONTROL, Bretigny-sur-Orge, France.
- EUROCONTROL (1998) Air Traffic Management Strategy for 2000+, Volumes 1&2, EUROCONTROL, Belgium.
- EUROCONTROL (1999a) Model simulation of Bulgarian airspace, EEC Note 4/99, Project SIM-F-E1 (F7), ATM Operational & Simulation Expertise Group, EUROCONTROL, Bretigny-sur-Orge, France.
- EUROCONTROL (1999b) Model Simulation of the Czech Republic Airspace, EEC Note 5/99, Project SIM-F-E1 (F24), ATM Operational & Simulation Expertise Group, EUROCONTROL, Bretigny-sur-Orge, France.
- EUROCONTROL (1999c) Central Europe fast time simulation, EEC Note 3/99, Project SIM-F-E1 (F18), ATM Operational & Simulation Expertise Division, EUROCONTROL, Bretigny-sur-Orge, France.
- EUROCONTROL (1999d) RAMS Simulation of Warsaw FIR, EEC Note 13/99, Project SIM-F-E1 (F28), ATM Operational & Simulation Expertise Division, EUROCONTROL, Bretigny-sur-Orge, France.
- The Financial Times (1999) EU calls for unified air traffic control, Thursday 2 December.
- Fischer, C. and R. Seaman (2001) Summary and Evolution of the Good Sectorisation Rules from TOSCA II, The European OneSky Project, **ONESKY/WP1/NAT/W0001;1.1**
- Gawron, V.J., Scheflett, S.G. and J.C. Miller (1989) Measures of in-flight workload, in R.S. Jensen (ed.) *Aviation Psychology*, 240-87, Gower: Brookfield, Virginia.
- Geisinger, K. and B. MacLennan (1994) Sector Design Analysis Tool (SDAT) Workload Model Design Document, Operations Research Service, AOR-200, Federal Aviation Authority, USA.
- Geisinger, K (1995) Proposed SDAT task load model validation plan, ASD-430, Federal Aviation Authority, USA.
- Greene, W.H. (1997) *Econometric analysis*, Prentice-Hall International, Inc., London.
- Gujarati, D.N. (1995) *Basic econometrics*, McGraw-Hill Inc., UK.
- Haining, R. (1990) *Spatial data analysis in the social and environmental sciences*, Cambridge University Press, Cambridge, U.K.
- Hart, S.G. and Staveland, L.E. (1988) 'Development of the NASA-TLX (Task Load Index): Results of empirical and theoretical research.' In P.A. Hancock and N. Meshkati, *Human Mental Workload*, North-Holland.
- Hook, M.K. (1993) PUMA version 2.2 User Guide, Roke Manor Research Ltd. Internal Report, X27/HB/1320/000.
- Hopkin, V.D. (1995) *Human factors in air traffic control*, Taylor & Francis, London.
- Issaks, E.H. and R.M. Srivastava. (1989) *Applied geostatistics*, Oxford University Press, Oxford, U.K.
- Jorna P.G.A.M (1991) Operator workload as a limiting factor in complex systems, Automation and Systems Issues, (eds.) J. Wise and D. Hopkin, NATO ASI series.

- Journel, A.G. and C. J. Huijbregts (1978) *Mining geostatistics*, Academic Press, London :UK.
- Lamoureux, T. (1999) The influence of aircraft proximity data on the subjective mental workload of controllers in the air traffic control task, forthcoming, *Ergonomics*.
- Lange, D G F (1989) *The Crisis of European Air Traffic Control: Costs and Solutions* Wilmer, Cutler and Pickering, London/ Brussels/ Washington DC
- Laudeman, I.V., Shelden S.G., Branstrom, R. and C.L. Brasil (1998) Dynamic Density: an air traffic management metric, NASA-TM-1998-112226, April 1998.
- Lyons, A.R. and M.G. Shorthose (1993) Capacity indicators study; Report on Phase 2, C/1013/CE/92, Smith System Engineering Limited, Guildford, England
- Magill, S. A. N. (1997) Trajectory predictability and frequency of conflict-avoiding action, Paper presented at the CEAS 10th International Aerospace Conference, Amsterdam, the Netherlands, 1997.
- Magill, S. A. N. (1998) The effect of direct routing on ATC capacity, Paper presented at the 2^d Europe/ USA Air Traffic Management R&D Seminar, Saclay, France 17-20 June, 1997.
- Mogford, R.H., J.A. Guttman, S. L. Morrow and P. Kopardekar (1995) *The complexity construct in air traffic control: a review and synthesis of the literature*, DOT/FAA/CT-TN92/22, Department of Transportation/ Federal Aviation Administration Technical Center, Atlantic City, NJ.
- Richmond, K. (1995) Personal communication.
- Rodgers, M.D., Mogford, R.H. and L.S. Mogford (1998) The relationship of sector characteristics to operational errors, FAA Report DOT/FAA/AM-98/14.
- Sridhar, B., Sheth K.S. and S. Grabbe (1998) Airspace complexity and its application in air traffic management, Paper presented at the 2nd. USA/EUROPE Air Traffic Management R&D Seminar, Orlando, Florida, December 1998.
- Stamp, R.G. (1990) The Assessment of airspace capacity, Speaking notes to the Royal Aeronautical Society Conference, London.
- Stamp, R.G. (1992) The DORATASK method of assessing ATC sector capacity - an overview, DORA Communication 8934, Issue 2, Civil Aviation Authority, London.
- Upton, G.J.G. and B. Fingleton (1985) *Spatial data analysis by example, Volume 1: Point pattern and quantitative data*, Wiley, Chichester, U.K.
- Verbeek, M (2000) *A Guide to Modern Econometrics*, John Wiley & Sons Ltd, Chichester, England:UK.
- Wickens C.D., A.S. Mavor. and J.P. McGee (Eds) (1997) *Flight to the Future: human factors in air traffic control*, National Academy Press, Washington DC, USA.
- Wickens, C.D. (1992) Engineering psychology and human performance, Harper Collins, USA.
- Gourieroux, C., Monfort, A. and Trognon, A. Pseudo maximum likelihood methods: applications to Poisson models. *Econometrica*, 52, pp. 701-720. 1984.
- Heydecker, B.G, Wu, J. (1999). Identification of sites for road accident remedial work by Bayesian statistical methods: an example of uncertain inference. The Fifth International Conference on the Application of Artificial Intelligence to Civil and Structural Engineering, Oxford.
- Hauer E. (2001) Overdispersion in modelling accidents on road sections and in Empirical Bayes estimation, *Accident Analysis & Prevention*, Volume 33(6), pp. 799-808.
- Hausman, J.C., Hall, B.H. and Griliches, Z. Econometric models for count data with an application to the patents-R&D relationship. *Econometrica*, 52(4), pp. 909-938. 1984.
- Maycock, G., Hall, R.D. Accident at 4-arm roundabouts. LR 1120. Transport and Road Research Laboratory, Crowthorne, Berks, U.K. 1984.
- Miaou, S.-P. The Relationship Between Truck Accidents and Geometric Design of Road section: Poisson versus Negative Binomial Regression. *Accident Analysis and Prevention*, 26(4), pp. 471-482. 1994.
- Shankar, V.N., Mannering, F. and Barfield, W. Effect of Roadway Geometric and Environmental Factors on Rural Freeway Accident Frequencies. *Accident Analysis and Prevention*, 27(3), pp. 371-389. 1995.
- Vogt, A. and Bared, J. Accident models for two-lane rural segments and intersections. *Transportation Research Record*, 1635, pp. 18-29. 1998.

Table 4. A comparison of the alternative air traffic controller workload models.

	SDAT	CIM	DORATASK	RAMS	PUMA
<i>Developer</i>	FAA (USA)	EUROCONTROL	CAA (UK)	EUROCONTROL	CAA(UK)
<i>Type</i>	Analytic	Analytic	Simulation	Simulation	Simulation
<i>Task data source</i>	Input and output messages of the HOST/SAR computer system tapes; Observer data; Facility voice tapes.	European ATC Reference tasks	UK Reference tasks based upon controller observation	European ATC Reference tasks based upon controller observation	Observational task analysis (OTA) - including cognitive debrief
<i>Controller</i>	Planning and Radar	Radar	Radar, adapted to planning and radar	Planning and Radar	Can adapt for both planning and radar.
<i>Taskload differentiation</i>	Good routine tasks; Probabilistic Conflict resolution; Accounts for sector scanning and planning tasks.	Good routine tasks; Probabilistic Conflict resolution; Accounts for monitoring tasks.	Good routine tasks; Simulates for determine conflict detection / resolution; Accounts for sector scanning and planning tasks.	Good routine tasks; Simulates for determine conflict detection / resolution; Accounts for some scanning and planning tasks/ no general monitoring; Good coordination tasks.	Excellent modelling of cognitive aspects of the controllers' tasks; Should be able to account for all tasks done by a controller - observable and non-observable.
<i>Validation and use</i>	US only, validation being undertaken.	European airspace sectors, validation compared to EAM results.	Validated for several UK airspace sectors.	Together with EAM, validated for Europe's airspace.	Validation still in progress
<i>Strengths</i>	Requires little or no manual input from the SDAT user - thus no need for manual data collection and no guess work on the users part; Useful for rapidly determining the workload of controllers in a sector when compared to full	Incorporates information about the intrinsic complexity of the airspace in deriving workload; Enables airspace design issues to be explored more rapidly than possible with a full scale fast time or real time	Most suitable simulation of controller workload for the UK's airspace. The task modelling and workload calculation are the most appropriate for the UK.	Widely used and validated throughout Europe for different European airspace sectorisations; A very flexible model and relatively easy to use.; The teamwork aspect of ATC relatively well modelled; Good conflict resolution	Only model which considers the cognitive processes of the controller; Models controllers undertaking more than one tasks simultaneously. Has been used to some extent in the European

	scale fast time or real time simulation.	simulation; Applicable to any region of airspace in which controller workload provides the major limiting factor on airspace capacity.		mechanism based upon rules for European airspace . Level of detail in the RAMS simulation is greater than that for DORATASK?	context for improving real-time and fast-time models.
<i>Weaknesses</i>	Largely limited to what can be determined or inferred from the recorded SAR data, which is only a sub-set of the entire task load of the controller; assumes that no tasks are performed simultaneously and that all task actions occur when the data were recorded by the HOST - not necessarily always the case; Limited to historic analysis of sector data, so cannot be used for planning future traffic scenarios.	Assumes that the airspace has a fixed route structure, and does not address the capacity limitations for a dynamic environment; Cannot treat “knock-on” conflicts, involving more than two aircraft; Cannot model the controller undertaking two or more tasks simultaneously.	Cumbersome model requires considerable effort is ensuring the calibration of the parameters.; Suitable only for use in the UK.; Cognitive tasks are not accounted for; Assumes that two tasks cannot be carried out simultaneously.	Does not appropriately account for the cognitive aspects of air traffic control; Assumes that two tasks cannot be carried out simultaneously.	Cumbersome model - OTA difficult to do; Any change from base case requires new OTA and real-time simulations; Not fully validated for use.

Figure 5. The Analytical framework for assessing the conflict count data

