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Traffic Law
Review
U. D. C.: 656.7.001.25:681.5
Accepted: Nov. 11, 2000
Approved: Mar. 13, 2002

THEORETICAL MODEL FOR DETERMINATION OF AIRSPACE CAPACITY

ABSTRACT

In the last decade, the constant air traffic growth has brought certain problems as well. While aircraft production and airline functioning are being stimulated by the competition, the situation in air traffic control and in infrastructure component is completely different. Air traffic management (ATM) is still owned by the state. The state, however, is known for the fact of not being a good manager and is solving problems slowly and not efficiently because of its large administration. There is a very strong trade union movement functioning in ATM, which makes several rational decisions impossible. Critics of the current ATM system in Europe warn of increasing problems - delays and operational expenses. The control component is the only one among the four components of air traffic, which has not been liberalised and harmonised yet. There is no competition in the fields of air traffic. All matters are taken care of by CAA or by semi-private companies, owned by the state. According to air carriers which have to put in 4-9% of business expenses into terminal - and over-flight charges, these expenses are far too heavy a burden.

KEY WORDS

airspace capacity, air traffic flow

1. AIRSPACE CAPACITY AS THE MOST IMPORTANT AIR TRAFFIC FLOW FACTOR

In the air traffic and more precisely in the ATS[1] the term »capacity« cannot be treated equally to its use in industry or other traffic subsystems. The reason for this is the so-called human factor on the one hand and the fact that flying is an unfamiliar movement to mankind on the other. There are two serious interferences, which grow as a non-linear function and cause disturbance in normal system operations.

Human factor (an air traffic controller in this case) has his own limits and capabilities, which are subordinated to other, subjective conditions and this leads to the following distinctions:

- among the abilities of individual controllers,
- among the abilities of a certain controller on different occasions.

These factors are only two among many and yet can prevent capacity from being defined as the maximum hourly flow rate, because some controllers will be able to achieve this, while others will not (or perhaps a certain team will achieve it once, but not for the second time).

The second obstacle exposes the human factor even more. In case of air traffic congestion, the aircraft are not capable of stopping and waiting for the situation to calm down, and when possible, continue to move in their planned direction (in other transport modes, this is possible). When compared to other means of transport aircraft can only fly within a certain range of velocity, which is subordinated to altitude, weather conditions and the mass of aircraft. At the same time, an aircraft has a limited range or time limitation of individual flight, which is again subordinated to several parameters.

Determination of maximum constant or periodical air traffic flow through a certain ATC-sector is a technique which has to take the following three essential elements into consideration:

- **Safety** is the most important factor, since capacity growth should not and cannot be a factor of increase in safety hazard.
- **Efficiency** which has two important factors:
  - Efficiency significant for air carriers; which refers to as few delays and re-routing as possible, and the least expensive air traffic service possible.

- Efficiency significant for ATS; which refers to gaining sufficient amount of means by selling their service.
- **Workload level** of air traffic controllers. Operational staff should not be overburdened, because this could lead to unreliability and mistakes in day-to-day work.

The highest demand depends on daily, weekly and seasonal oscillations. From time to time there is an additional demand, for example: big sport events, air supply to Bosnia and Herzegovina and to Albania, when the demand was greatly increased, as a large number of military and civil aircraft co-operated in those operations.

In addition to the noted oscillations there are distinctions in demand of different flight headings and flight levels. The reason for this is the air traffic congestion on a few flight levels – for economical reasons modern jets are using highest possible flight levels.

»ATS-sector capacity is the rate of the maximum air traffic flow in a certain period of time, expressed in number of aircraft. According to ICAO standards and recommendations this assures a certain safety hazard rate regarding workload level of air traffic controllers and capability of technical equipment for normal air traffic control operations.«

It is impossible to distinguish between objective and subjective influences on airspace capacity. However, both influence greatly the present local and wider European air traffic.

1.1 Capacity and optimal ATS-sector size determination

The only correct method for determination of capacity and optimal ATS-size determination is the computer model design (although several theoretical and practical methods exist). The computer model is used to simulate different air traffic flows. This procedure is based on distinctive sector shapes and sizes and configuration of airways. Simulation results need to be analysed and the final results need to be tested in the air traffic control simulator.

To determine capacity, workload level of air traffic controller and optimal airspace configuration, the following models and methods can be used:

- Practical methods for determining sector size and capacity;
- Theoretical methods for determining sector size and capacity.

1.2 Theoretical methods for determining air traffic capacity

Theoretical methods that are nowadays most frequently used are:

- **DORA method;**
- **Real time simulation method;**
- **Fast time simulation method;**
- **Subjective Workload Assessment Techniques;**
- **Voice Channel Utilisation Analysis;**
- **Physiological Measurements;**
- **Time Summation;**
- **Eurocontrol model for flow maximisation;**
- **Waiting lines;**
- **Mathematical model.**

3.1 Analysis of implementation of theoretical methods and models

However, the methods used for determining sector and ATM capacity within ATS are not sufficient for accurate, quick and reliable implementation. Only the correct combination of the methods mentioned above shows the true capability of individual ATM units. This is accomplished by using computer technology and also testing on ATC simulator. Therefore, a comparison of method usage is appropriate.

The table below shows the usage of methods for individual parameters, which are important to enhance the capacity and airspace organisation planning.

The table proves that none of the methods are appropriate for the measurement of the ATS sectors capacity. Therefore, it is essential to design a model, which is open and useful for several purposes. The model should enable different configurations of airway network, flow simulation and it should calculate the maximum capacity of a given configuration.

2. AIRCAMPO MODEL

AIRCAMPO model was designed to prove the author's thesis, which states that only larger sectors (in upper airspace) enable a larger flow. The author tried to find the basic mathematical or computer model in other countries, but that was not possible. It turned out that such a model for determination of capacity in upper airspace could be designed in Slovenia. The model would also be useful for several strategic and tactic air traffic control activities.

2.1 Design of the model

In the past years, some representatives of CAA Slovenia and the Ministry of Transport have invested great efforts into proving the nonsense of further development of the system for air traffic control in the upper airspace. Others have been trying to prove that further work on one's own system is the only feasible strategy for the future. The struggle between these two options was the reason that CAA Slovenia invited

Table 1 - Use of methods for determining some ATS operation parameters

Method \ Objective	Capacity	Testing changes in airspace organisation	Accuracy	Speed	Safety Risk
Practical methods for sector determination of size and capacity	/	/	–	–	/
DORA model	/	+	/	–	+
Real time simulation method	/	+	/	–	+
Fast time simulation method	/	/	/	+	+
Subjective Workload assessment techniques	–	–	–	+	/
Voice Channel Utilisation Analysis	+	+	/	/	/
Physiological Measurements	–	/	/	–	+
Time Summation	/	+	/	–	+
Waiting lines	/	–	–	+	–
Mathematical Model	/	+	+	–	+
Eurocontrol model for flow maximisation	/	–	/	+	+

Note: + positive,
– negative,
/ useful under certain condition.

applications for a project assignment to design a computer model. The firm ENSICO offered its services and the offer was accepted. The whole design process took four months. However, the model can still be rearranged in details, if individual needs of CAA Slovenia would require this. The model works in the Windows environment and can be used on a common personal computer. As the model is based on a realistic geographical network, it is possible to determine geographical co-ordinates of each point of a rough scheme in between.

The model covers a limited area and the reason for this is the relation between distances in nautical miles and distances in geographical degrees on the map. The basics of the geodetic reference is WGS 84, which makes it compatible with the GPS system.

2.2 Basic model algorithm

If configuration of airspace is given, the model calculates the airspace capacity and the workload level of air traffic controller. The capacity is determined by means of several calculation iterations. Although several iterations indicate better accuracy, the model indicated that only ten iterations suffice to determine an average. With results given by the model, the capacity of a certain airway and a certain airway crossing can be determined.

Results of the model operations:

- maximum, minimum and average number of aircraft entering the sector,
- number of aircraft leaving the sector,
- number of every controller-staff contact,
- number of contacts with the task of preventing potential collisions,
- changes of altitude or heading on pilot's demand.

All the data are noted also at the level of each airway separately.

2.2.1 Algorithm

Algorithm consists of two sections:

1. **primary section**, which looks for potential controller's intervention,
2. **secondary section**, which does away with safety hazard regarding the threat of the minimum separation allowed.

2.2.1.1 Primary section of the algorithm

1. Searching for the first point of potential controller's intervention (VOR, new aircraft on airway, catching up or collision of two aircraft.
2. Doing away with safety hazard.
3. In case the first potential controller's intervention is on VOR or on airway entry/exit point, new aircraft positions are set. By doing so sometimes the airway level (altitude) has to be changed (if the pilot's demand is such). It is possible to check whether the aircraft will or has already changed its direction of flight.
4. It is possible to check if any aircraft is in waiting lines. If so, the aircraft can perhaps be headed back to the airway.

2.2.1.2 Secondary section of the algorithm

1. Checking whether a potential collision is more likely to happen on different airways or on the same airway.
2. Attempt of slowing down an aircraft. If not possible, flight level is changed. The last alternative is to send the aircraft into waiting line (holding out of routes).

2.3 Solving potential conflicts

When a problem of a potential conflict arises, navigational capabilities of the aircraft need to be considered. Calculations that solve potential conflicts are given at the end of this chapter.

2.3.1 Potential collision

As the model recognises a potential collision, it reacts as stated below:

1. tries to change the speed of the aircraft,
2. tries to slow down the aircraft, which flies »zigzag«,
3. changes the flight level,
4. sends the aircraft into waiting lines.

Inbound airway crossing or entry/ exit point

If the first controller's intervention is on entry point at the sector border or at the crossing, new aircraft positions are determined. If necessary, the flight level is changed. The model checks whether the aircraft is going to change its heading. If this happens, the model changes the heading of the flight (on pilot's or controller's request).

Calculation of time, in which a minimum distance between two aircraft is attained

$$x_1 = x_{10} + v_1 t \cos\varphi_1 \quad x_2 = x_{20} + v_2 t \cos\varphi_2$$
$$y_1 = y_{10} + v_1 t \sin\varphi_1 \quad y_2 = y_{20} + v_2 t \sin\varphi_2 \tag{1}$$

Aircraft position to time

$$d = \sqrt{(x_{10} - x_{20} + t(v_1 \cos\varphi_1 - v_2 \cos\varphi_2))^2 + (y_{10} - y_{20} + t(v_1 \sin\varphi_1 - v_2 \sin\varphi_2))^2} \tag{2}$$

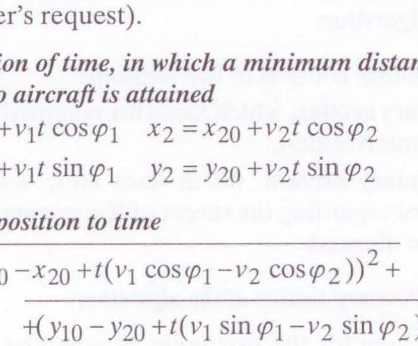

Figure 1 - Approach of aircraft

Distance between two aircraft

Within the point of extreme one determined $\dot{d} = 0$

$$t = \frac{(x_{10} - x_{20})(v_1 \cos\varphi_1 - v_2 \cos\varphi_2)}{2v_1 v_2 \cos(\varphi_1 - \varphi_2) - v_1^2 - v_2^2} + \frac{(y_{10} - y_{20})(v_1 \sin\varphi_1 - v_2 \sin\varphi_2)}{2v_1 v_2 \cos(\varphi_1 - \varphi_2) - v_1^2 - v_2^2} \tag{3}$$

Time, in which the minimum distance between two flights is achieved

2.3.2 Calculation of the nearest still acceptable position

t = time (calculated above)

k, a = parameters of the straight line, which represent the movement of the aircraft

Definition: $$t_1 = v_1 \cos\varphi_1 - v_2 \cos\varphi_2 \qquad t_2 = v_1 \sin\varphi_1 - v_2 \sin\varphi_2 \tag{4}$$

$$d = \sqrt{\left(x - x_{20} + \frac{(x - x_{20})t_1^2 + (kx + a - y_{20})t_1 t_2}{t_1^2 + t_2^2}\right)^2 + \left(x - x_{20} + \frac{(kx + a - y_{20})t_2^2 + (x - x_{20})t_1 t_2}{t_1^2 + t_2^2}\right)^2} \tag{5}$$

Definition:

$$a_1 = \frac{t_1^2 + k t_1 t_2}{t_1^2 + t_2^2} + 1, \qquad b_1 = \frac{(a - y_{20})t_1 t_2 - x_{20}(2t_1^2 + t_2^2)}{t_1^2 + t_2^2},$$
$$a_2 = \frac{k t_2^2 + t_1 t_2}{t_1^2 + t_2^2} + 1, \qquad b_2 = \frac{(a - y_{20})t_2^2 - x_{20}(t_1^2 + t_1 t_2 + t_2^2)}{t_1^2 + t_2^2} \tag{6}$$

The following equation is in usage:

$$0 = (x a_1 + b_1)^2 + (x a_2 + b_2)^2 - d^2$$
$$x_{1,2} = \frac{-(a_1 b_1 + a_2 b_2) \pm \sqrt{D}}{a_1^2 + a_2^2} \tag{7}$$
$$D = (a_1 b_1 + a_2 b_2)^2 - (a_1^2 + a_2^2)(b_1^2 + b_2^2 - d^2)$$

For the x position we have to use appropriate x:

Equation of still allowed x-position of aircraft

2.3.3 Calculation of slowing down due to zigzag flight

k = turn rate (k=PI/180 radian/second)

d = width of airway (18,520m)

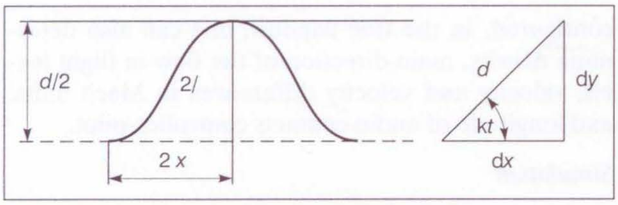

Figure 2 - Zigzag flight

$$dl = vdt = \frac{dx}{\cos kt} = \frac{dy}{\sin kt} \tag{8}$$

$$\sin(kt)dt = \frac{dy}{v}$$

$$\int_0^t \sin(kt)dt = \int_0^{d/4} \frac{dy}{v} \tag{9}$$

$$t = \arccos\left(1 - \frac{kd}{4v}\right); \quad v > \frac{kd}{4}$$

Minimum time for flying one quarter of the width of airway

$l = vt$

$$l = \frac{v}{k}\arccos\left(\frac{1-kd}{4v}\right) \tag{10}$$

Distance flown in time-t

$dx = v\cos(kt)dt$

$$\int_0^x dx = \int_0^t v\cos(kt)dt \tag{11}$$

$$x = \frac{v}{k}\sin\left(k\arccos\left(1 - \frac{kd}{4v}\right)\right)$$

Distance in time-t with a maximum turn rate

2.4 User's interface

Characteristics of the model are the following:

When the program is started with air.exe, one can detect:

- console window for checking the server connecting status – debug support;
- console window of the model, which switches on automatically together with the user's interface – debug support;
- tree window with data of airways, performances of aircraft and skills of the controllers;
- map for graphical drawings and sector boarders with the use of a mouse

Configuration can be set through tree structure by clicking a certain complex. Properties (right) are the data, which determine certain elements of the tree. Names of data are given in the left column, and data values in the right column.

Tree Window

It is used for installing and checking data

Map window

The map window enables addition of airways and VOR and determination of the sector shape with the use of mouse. The main part of the window is a map of Slovenia, where the user marks the sector, VOR and airways. Buttons below: Zoom OUT, Zoom IN, Refresh; Buttons on the right: Load sector, Save sector,

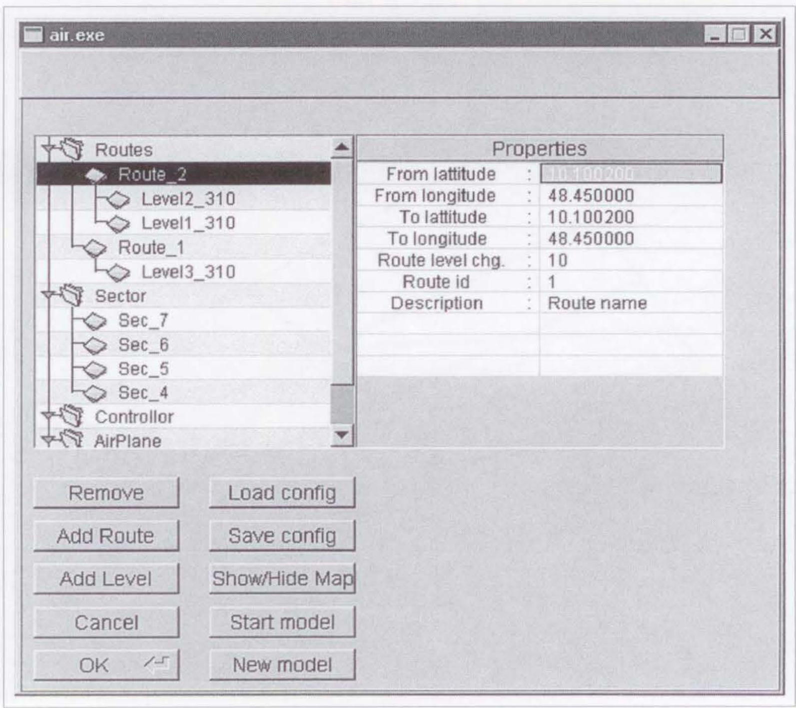

Figure 3 - Tree window of the model

Load routes, Save routes, Close sector, and the menu »draw routes/sector/VOR«. Pressing the Zoom OUT button switches to a map of Slovenia in a small-scale model (with some already mentioned restrictions).

(Map window with already entered airways is presented in Chapter 3.)

Print of simulation results

The model transforms the print of simulation results directly to Microsoft Excel. There is a print for each distinctive airway and for the whole sector. All the results lie within a sixty-minute time frame. Due to random setup and overflight calculations, the results are shown as minimum, average and maximum. Registered results are:

The minimum, average and maximum number of:

- aircraft at entry point to sector and airway,
- aircraft at exit point of sector and at the end of airway,
- established audio contacts between controller and staff.

The number of routine and critical contacts is accurately measured. For processing data without further complication, the model registers the results in Excel as well.

3. COMPUTER SIMULATION OF AIR TRAFFIC FLOW

For certain simulations, an airway network, radio-navigational equipment and sectors need to be configured. In the tree window, one can also determine density, main direction of the flow in flight levels, velocity and velocity differences in Mach units, and longitude of audio contacts controller-pilot.

Simulation

Number of airways: 6
Number of crossings: 6
VOR positions: 2
15° 08,13'
46° 15,19'
16° 16,66'
45° 30,37'
Flight level changes: no demands
Velocity in Mach units: 0,85
Difference in velocity in %: 10
Sector borders:
13° 36,18', 47° 21,25'; 17° 59,15', 45° 39,81'; 17° 01,76', 44° 47,12'; 12° 26,49', 46° 10,87'.
Traffic on each airway
A - 4/2/2; B - 4/3; C – 2/3/3; D – 1/2; E - 2/3/2; F – 1/2/4; G – 4/5/4[2]

4. RESULT ANALYSIS

As many times before, it is essential to stress again that simulations give satisfactory results only when studying the upper flight levels. Study of the lower flight level demands smaller sectors (because of much bigger differences in velocity of aircraft and more vertical movement of aircraft).

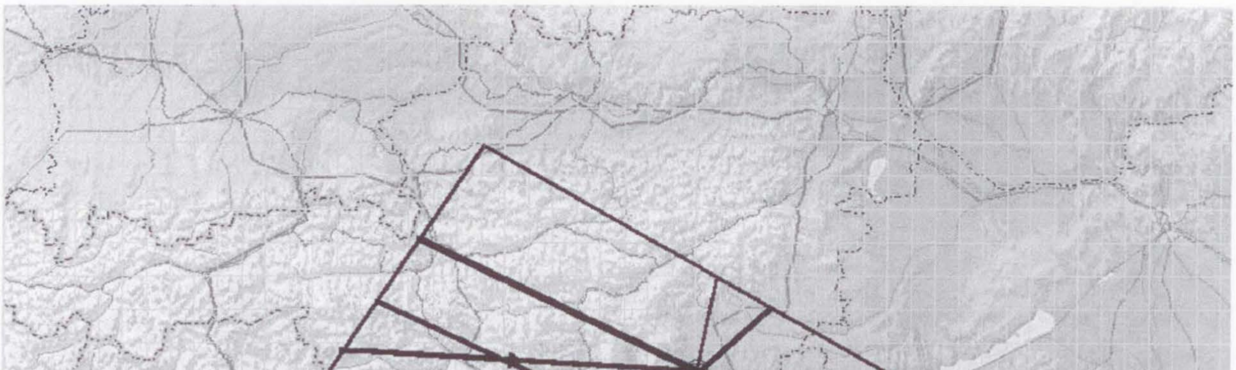

Figure 4 - Sector CEATS

Table 2 - Simulation results

Route ID	6	6	6	5	5	4	4	4	4	4	4	3	3	2	2	2	1	1	1
Plane in	2	2	2	4	2	4	1	1	0	0	0	0	1	4	1	0	1	3	1
Plane out	1	2	2	3	2	3	1	2	1	1	1	0	1	4	0	0	1	3	1
All contacts	3	4	4	7	4	7	2	3	1	1	1	0	2	8	1	0	2	6	2
Critical contacts	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plane contacts	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Min Plane in	1	2	2	3	2	3	1	1	0	0	0	0	1	3	1	0	1	2	1
Min Plane out	1	2	2	3	2	3	1	1	1	1	1	0	1	3	0	0	1	3	1
Min All contacts	2	4	4	6	4	6	2	2	1	1	1	0	2	6	1	0	2	5	2
Min Critical contacts	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Min Plane contacts	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Max Plane in	3	4	4	5	4	5	3	3	0	0	0	1	2	5	2	1	2	4	2
Max Plane out	2	3	3	4	3	4	2	3	1	1	1	1	2	5	1	1	2	3	2
Max All contacts	5	8	7	9	7	10	5	7	1	1	1	2	4	11	3	3	4	7	4
Max Critical contacts	0	1	0	0	0	1	0	1	0	0	0	0	0	1	0	1	0	0	0
Max Plane contacts	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plane in	37																		
Plane out	35																		
All contacts	74																		
Critical contacts	2																		
Plane contacts	1																		
Min Plane in	33																		
Min Plane out	33																		
Min All contacts	66																		
Min Critical contacts	0																		
Min Plane contacts	0																		
Max Plane in	42																		
Max Plane out	37																		
Max All contacts	85																		
Max Critical contacts	4																		
Max Plane contacts	6																		

When analysing a simulation, air traffic control can take place. The Voice Channel Utilization is the only obstacle: Routine tasks – the controller-pilot data connection, when taking over or giving away responsibility. At maximum overload in a very simple ATS sector with 65 aircraft per hour in the first simulative complex a controller-pilot data connection takes 75% of the time, which is bearable due to American judgement.

The first general finding:

Yes for larger sectors. Of course, the controller- -pilot data connection will have to come to use as soon aspossible to lessen the routine work in air traffic control.

The second finding:

As little complex crossings in ATS sectors as possible are to be implemented (they can cause potential conflicts). The two solutions are: optimal planning of air traffic flow direction in global sense and a long-term solution, implementation of Free Flight system.

Due to simulation results, a wider use of the model could come to use. The model can be used to satisfy two essential purposes:

- strategic research of airway configuration, size of ATS sectors, number of working stations, etc.
- tactical or operational research in connection with FMP in several centres for air traffic control.

Of course, the development of the model will continue and therefore increase its use. The first modification will take place in the area of calculating the capacity with implementation of Free Flight procedures.

POVZETEK

Stalna rast zračnega prometa v zadnjih 10 letih prinaša tudi določene težave. Medtem ko proizvodnjo letal in delovanje letalskih prevoznikov stalno spodbuja konkurenca, je to na področju kontrolne komponente, v manjši meri pa tudi na področju infrastrukturne komponente, drugače. Službe zračnega prometa v celoti so navkljub nekaterim uspehom pri komercijalizaciji in privatizaciji še vedno večinoma v državni lasti. Država pa je dokazano slabši gospodar, saj zaradi prevelike administracije probleme rešuje počasneje in slabše. V službah zračnega prometa deluje zelo močno sindikalno gibanje, ki marsikatero racionalno odločitev in strateško usmeritev celo onemogoči. Kritiki sedanjega sistema služb zračnega prometa v Evropi svarijo pred naraščajočimi problemi, predvsem zamudarni ter vedno večjimi operativnimi stroški opravljanja the storitev. Navajajo, da od štirih stebrov zračnega prometa, le kontrolna komponenta še ni okusila liberalizacije in harmonizacije. Na področju služb zračnega prometa in konkurence, zadeve pa rešujejo državne ustanove (civilne letalske uprave) ali pa polprivatizirana podjetja, katerih lastnik je seveda država. Prevozniki, ki za preletne ter priletne takse namenijo 4-9% celotnih stroškov poslovanja, trdijo, da jim ta strošek pomeni preveliko finančno breme.

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2. G - means continuation of airways A and mixing traffic from A and C

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